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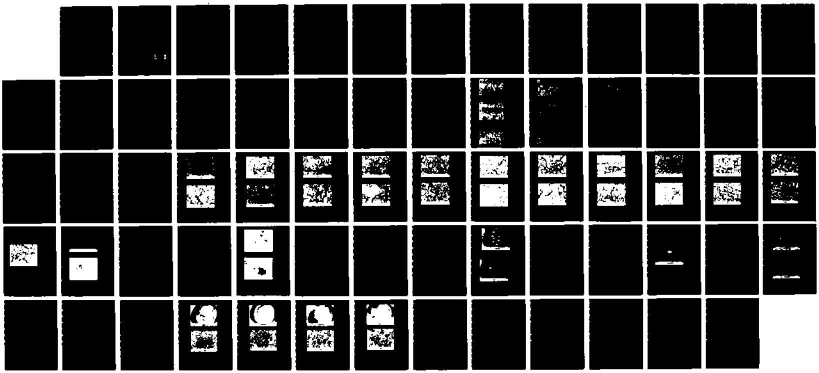

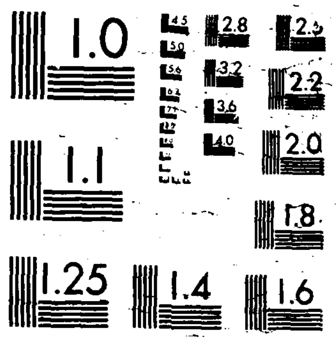
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MTL TR 86-44

THE EFFECT OF AUSTENITIZING CONDITIONS ON THE ANISOTROPIC EMBRITTLEMENT OF ESR 4340 STEEL

October 1986

E. G. HAMBURG and A. D. WILSON
Lukens Steel Company
Research Center
Coatesville, PA 19320

FINAL REPORT

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ABSTRACT

The effect of austenitizing conditions on the anisotropic embrittlement of electroslag remelted (ESR) 4340 steel were studied. Increasing austenitizing temperature from 1550°F to 1750°F had little or no effect on the strength and toughness of ESR melted 4340 steel. Decreasing the quench rate from 1000°F per minute to 500°F per minute had no effect on the strength and toughness. Decreasing the quench rate from 500°F per minute to 100°F per minute had a significant effect on Charpy V-notch toughness. Lower Charpy V-notch toughness associated with the quench rate of 100°F per minute was due to the presence of bainite in the microstructure. The presence of bainite had a small effect on slow bend fracture toughness. Plate anisotropy was very small in the plane of the plate (longitudinal versus transverse). Properties normal to the plane of the plate were affected drastically. Charpy V-notch toughness was decreased as much as 56% over the values obtained in the longitudinal direction. Reduction in area of the mild notch tensile specimen was decreased as much as 64% in the through-thickness direction when compared to the longitudinal direction. Inclusion clusters were primarily alumina with some calcium present. In all the tests conducted, there was no evidence for anisotropic embrittlement of this material (i.e., intergranular fracture).

INTRODUCTION

Electroslag Remelted (ESR) processed, high hardness (55HRC) 4340 steel has been reported to exhibit superior ballistic properties for armor applications[1,2]. These benefits are primarily due to the low sulfide inclusion content resulting from ESR processing. However, other studies have raised a concern of anisotropic embrittlement* of this steel during heat treatment, particularly in the short transverse orientation[3]. To investigate the potential influences of heat treatment on this embrittlement, a thorough study was undertaken. The study investigated austenitizing temperatures of 1550, 1650 and 1750^{o} F (843, 899, 954^{o} C) and quenching rates of 100, 500 and 1000 ^{o}F/min. (56, 278, 555 ^{o}C/min.). These levels were felt to reflect the full range of practices that may be used in heat treating this steel. The influences of these heat treatments on the tensile, Charpy V-notch (CVN), impact toughness and K_{Ic}, fracture toughness were evaluated in the three major testing orientations for a one-half inch thick ESR 4340 plate. Comprehensive metallographic evaluations also accompanied this testing, including extensive scanning electron microscopic (SEM) fractography.

The benefits of ESR processing are often confirmed by a reduction in sulfur content to very low levels (less than 0.005 w/o). However, the reduction in overall inclusion content and morphology of the remaining inclusions also has a beneficial effect on behavior[4,5]. ESR processing involves remelting of a 4340 steel electrode through a molten slag, which chemically and physically removes

* Varying degrees of embrittlement depending on testing orientation.

the manganese sulfide and aluminum oxide inclusions that are present in conventionally produced steels. The molten steel is subsequently solidified in a copper water-cooled mold. The cooling rates in the mold tend to promote smaller, well dispersed inclusions, when compared to conventional ingot steel production. The remaining inclusions are also found to be calcium modified, when the refining slag contains CaO[5]. In particular, calcium aluminates are a primary inclusion found in ESR steels. Therefore in this study, to further identify the potential variables influencing the toughness of ESR 4340 steels, the non-metallic inclusions found on the tensile, CVN and K_{Ic} fracture surfaces were characterized.

To obtain specimens in the short transverse testing orientation, a novel cutting and welding of extension material was used prior to austenitizing and quenching of test plates. Although the hazards of quench cracking resulted in difficulty in obtaining specimens in all testing conditions, enough were successful to continue use of this procedure. These procedures will be discussed in more detail in the following sections.

MATERIALS AND PROCEDURE

An ingot of 4340 steel was electroslag remelted (ESR) to the chemistry shown in Table 1. A portion of this ingot was rolled to 1/2 inch plate for evaluation. The variables of concern are the effect of austenitizing temperature, cooling rate during quenching and the plate anisotropy resulting from the rolling process. Three austenitizing temperatures of 1550°, 1650° and 1750° for

1 hour were used on the material. Specimens were coded 15, 16 and 17, respectively. Nominal quench rates of 100^{o} F per minute (A), 500^{o} F per minute (P) and 1000^{o} F per minute (W) were carried out on the material. 1000^{o} F per minute was achieved by quenching into water, 500^{o} F per minute was achieved by cooling in a controlled air jet and 100^{o} F per minute was achieved by cooling in air.

Specimens were tempered between 340^{o} F and 390^{o} F for 1 hour to achieve uniform hardness of approximately 55 HR_c in all samples. Table 2 summarizes the heat treating and shows the resulting hardness.

Standard* Charpy V-notch samples and standard* 0.252 tensile samples were prepared and machined in the L-T** direction (L) and T-L** direction (T). Slow bend fracture toughness specimens** were prepared in the L direction only. Specimen blanks were prepared for testing in the short transverse direction by welding 1/2 inch thick extensions normal to the surface of the plate and then machining off the original plate excess. These blanks were then heat treated as described above. After heat treating, the blanks were then used to prepare standard CVN specimens with the notch oriented in the S-L (S) direction.

Fracture surfaces were examined using scanning electron microscope (SEM) and analysis of inclusion was carried out using energy dispersive X-ray analysis (EDXA).

* ASTM A370
** Per ASTM E399

RESULTS

Heat Treating and Microstructure

Table 2 exhibits the austenitizing temperature, quench rate, tempering temperature and Rockwell C hardness of the materials examined. The microstructures of the 3 cooling rates are shown in Figures 1, 2 and 3 in the quenched and tempered condition. For the W and P conditions the microstructures are 100% martensite. The A condition resulted in small amounts of bainite in the sample. It appears that the sample austenitized at 1650° F had approximately 10% bainite while the samples austenitized at 1750° F and 1550° F had less than 7% bainite. The bainite in Sample 16A was banded to a greater degree than in 15A and 17A.

The presence of a small amount of bainite when the cooling rate is 100° F per minute is expected. Calculations(6) of the critical cooling rate (CCR) for 100% martensite indicate that bainite can be expected for cooling rates less than 200° F per minute.

Mechanical Properties

Table 3 presents the results of tensile tests, Charpy V-notch toughness at ambient temperature (RT) and -40° F, and slow bend fracture toughness at RT. The tensile test results for standard specimens oriented in the short transverse direction (S) were invalid because the samples necked down in the weld region giving low strength and ductility. No test samples were obtained for 15 PS, 16 PS, 16 WS, 17 PS and 17 WS conditions because quench cracks developed in the sample blanks during heat treatment. Figure 4 compares yield strength and tensile strength of L and T samples only. The yield strength of the slow cooled samples (A) were significantly lower than the W or P samples. The effect of cooling rate on tensile strength was comparatively less. The water quenched samples (W) had the highest yield strengths.

Weld failures were experienced while tensile testing specimens oriented in the through thickness (S) direction. Therefore, mild notch sa ples were prepared from the remaining standard samples in order to compare the strengths and ductility in the three test directions. The notches were oriented in the welded section of the S sample so that the minimum diameter was located at the centerline of the plate. The specimens consist of a 3/8" diameter notch with a root diameter of 0.150". The 0.2 percent offset was estimated from the load elongation curve. Table 3 contains the test results. Figure 5 shows the reduction in area plotted as a function of tensile strength. The specimens oriented in the short transverse (S) direction exhibit significantly lower ductility than in the L and T direction. The reduction in area for the short transverse (S) direction was between 9.8% and 11.9%. As shown in Figure 6, the air cooled (A) sample exhibited consistently lower reduction in area in the L and T direction than the P or W samples (22.2% to 28.3% for the A samples versus 33.2% to 37.3% for the P or W samples).

The presence of bainite lowers the yield strength and the tensile ductility of air cooled samples. The lower strength of the bainite component together with the coarse carbides associated with its formation act as sites for premature void formation or fracture nucleation. Thus the lower ductility of the A samples.

Figure 7 presents the relationship between Charpy V-notch toughness at 70^{o} F and yield strength. The Charpy V-notch toughness at 70^{o} F showed behavior similar to the reduction in area behavior. Short transverse orientation at 70^{o} F exhibited values between 6 and 10 foot pounds. There appeared to be no effect of either cooling rate or austenitizing temperature for samples tested in the

short transverse direction. For the L and T samples, the A cooling rate had significantly lower toughness than cooling rates P or W, despite having a lower yield strength. For the P and W Charpy results at -40° F, the L and T orientation austenitized at 1550° F appeared to give slightly higher toughness than samples austenitized at 1650° F and 1750° F (Fig. 8).

Fracture toughness measured in the L direction showed very little variation with either cooling rate or austenitizing temperature. The A samples showed slightly lower values than the P or W samples and there appeared to be a slight increase in fracture toughness for the 1750° F austenitizing temperature. Figure 9 compares K_Q with Charpy V-notch toughness measured at 70° F in the L orientation. K_Q exhibits very little variation as compared to the Charpy V-notch variation.

METALLOGRAPHY

Fractography - CVN

Figures 10 thru 12 show the fracture surface of CVN samples 15 AS, 15 AT, 15 PT, 15 WT and 15 WS. The transverse (T) samples of the intermediate (P) quenched samples and rapidly (W) quenched samples are characterized by dimpled rupture (see Figs 11A and 11B). The "dimples" that developed have a large range in size. Generally, they are free of any detectable second phase particles. A few small inclusions, located on these surfaces, contained Al and Ca. The sample that was slow quenched (A) showed an increased amount of quasi-cleavage when compared to the P and W sample (see Fig. 10B). The fracture surface of the sample oriented in the S direction (Fig. 12) was characterized by dimpled rupture. However, in this case there was evidence that small inclusions were

involved in the development of the void. The inclusions contained primarily Al and in some cases a minor amount of Ca. Fig. 10A shows the fracture surface of the 15 AS sample and Fig. 12A and 12B gives the fracture surface of sample 15 WS.

The CVN fracture surfaces for the steels austenitized at 1650° and 1750° F are shown in Figs. 13 thru 16. In all cases, the fracture surfaces are characterized by dimpled rupture. Quasi-cleavage is present but is not a prominent feature. Inclusions were difficult to find.

Fractography - K_Q Sample

Figs. 17 thru 21 present the fracture surfaces of the slow bend fracture toughness (K_Q) samples at 1000X. The samples are a mixture of dimpled rupture and quasi-cleavage. The similarity between the fracture surface morphologies reflects the similarity between the fracture toughness values measured, despite the differences in microstructure of the A samples versus the P and T samples. The presence of bainite in the microstructure does not alter the fracture surface appearance significantly.

Inclusion Characterization

A sample of steel in the heat treated condition was sectioned and polished parallel to the L, T and S planes of the original plate. Very few inclusions were observed when viewing parallel to the L and T direction. Small clusters of inclusions were visible on the section parallel to the S direction. Fig. 22A shows a cluster from the S plane and Fig. 22B shows two inclusions from the center of this cluster at a magnification of 2600X. The duplex inclusion marked at A exhibited an EDXA spectrum (Fig. 23) containing Nb, Al, V and Ti. The light area is apparently an Nb carbo-nitride (CN) with V and Ti in solution and the dark area an alumina particle. The area marked B is primarily an alumina

particle containing a trace of calcium as shown by the spectrum shown in Fig. 24.

Fig. 25 shows a duplex Nb-Ti-CN. The area marked C is rich in Ti and Nb with a small amount of V (Fig. 26). Area D is apparently a Nb-CN with a minor amount of Ti and a trace of V in solution (Fig. 27). It is postulated that these particles form when the steel is in the molten state. The presence of alumina particles adjacent to the Nb-Ti-CN suggests that the alumina can act as a nuclei for precipitation of the Nb-Ti-CN during solidification. The area E in Fig. 25B is an alumina inclusion as shown by the EDXA spectrum in Fig. 28.

Fig. 29A shows the fine inclusion in the cluster in Fig. 25B at 2600X. The particle F in Fig. 29A contains primarily Al with Ca, Ce and Mg as trace elements (see Fig. 30). Fig. 29B presents a section parallel to the longitudinal section. Clusters of inclusions were not visible on this section. The inclusions were isolated and typical of the inclusions shown in Fig. 29B. The inclusion marked G, analysed by EDX-A, contained primarily Al and Ca as a minor constituent (see Fig. 31). The small tails shown adjacent to the inclusion marked H and shown at higher magnification in Fig. 32 contained Mn and S (Fig. 33). The Al, Cr and Fe peaks are matrix emissions from the steel or the adjacent alumina inclusion.

Fig. 34A contains views parallel to the transverse section. The inclusions marked J and K were alumina. The inclusion J contained small amount of Ca (see Fig. 35) while the inclusion marked K contained only Al (see Fig. 36). The inclusion marked L in Fig. 34B is apparently a Ti-CN with Nb in solution (Fig. 37).

Additional inclusion analysis generally followed the trends discussed above. The bulk of the inclusions were alumina, some contained small amount of

Ca. Rare earths (Ce) were sometimes detected as a trace element. Sulphides, when detected, were associated with larger alumina inclusions. In no case were any sulphide stringers located. Fracture surfaces of CVN specimens and notch tensile specimens were generally free of inclusions. When inclusions were found on these surfaces, they generally analyzed as alumina often containing Ca as a minor constituent. Sulphides were never located on the fracture surfaces. The only sample that had inclusions on the surface to any degree was the 15 AS notch tensile sample. These inclusions analyzed as alumina inclusions and no sulphides were detected.

The lack of inclusions on the fracture surfaces of the L and T CVN samples and the overall bulk cleanliness suggests that the toughness of the steel in the L and T direction is limited by microstructural features. Significant differances were found between the toughness (and ductility) of the slow cooled samples (A) and the intermediate cooled (P)-rapidly cooled samples (W). The slow cooled samples contained a small amount of bainite, while the more rapidly cooled samples were 100% tempered martensite.

Fractography - Notch Tensile Samples

The notch tensile samples fractured after necking down substantially. Final failure was characterized by classic cup-cone fracture. The reduction in area of the notch tensile sample was very sensitive to structural features that affect ductility at high hardness. Figure 38A shows the shear lip development in 15WS. The shear lip area was 49% of the final area in 15WS (Figure 35) as compared to a shear lip area that was 67% of the final area in 15WT (Figure 39). The flat area was characterized by a mixture of ductile dimpled rupture in 15WT and a mixture of quasi-cleavage and dimpled rupture in 15WS.

Initiation of fracture appears to have occurred at the center of the cup-cone and then progagated radially outward until the final failure was by shear. The initiation site appears to be the region of maximum hydrostatic tension in the center of specimen as predicted by the Bridgeman analysis. Note that there are small inclusions (alumina) in this area as shown in Figure 38B. The fracture in 15WT is primarily dimpled rupture (Figure 39B).

Figure 40 presents the fracture surface of 15AS. This sample contained planar arrays (bands) of bainite. The fracture surface was made up of a combination of ductile rupture and quasi-cleavage. Figure 41 displays the surface of 15AT. The fracture surface of 15AT is similar to 15AS except that the dimpled rupture regions are more deeply developed, indicating greater toughness or ductility.

Nucleation of the fracture in the notch tensile specimens occurred in the region that developed maximum hydrostatic tension (center of specimen). Fracture progresses radially outward from this region until final fracture occurs along planar developing maximum shear stress. Initiation occurs at the weakest component present. In the case of 15WS, this appears to be at small alumina inclusions. Initiation in 15WT appears to have occurred at some fine microstructural feature. The features were too fine to identify by SEM microscopy. In the case of 15AS and 15AT, initiation appears to be within a bainite grain. The high hydrostatic developed during necking caused bainite grains to fracture thereby initiating the fracture.

Examination of notch tensile sample fracture surfaces in the other heat treated condition confirmed the above results and conclusions. There was no evidence of anisotropic embrittlement.

DISCUSSION

The quench rates of 1000° F per minute and 500° F per minute resulted in material with similar microstructure and properties. Austenitizing temperature appears to have resulted in a slightly coarser grain size for 1750° F. The difference between longitudinal and transverse properties for these quenching conditions was very small. The slow quench rate resulted in the presence of a small amount of bainite in the microstructure. The presence of bainite had a significant effect on reducing the tensile ductility, Charpy V-notch toughness and to a lesser degree the fracture toughness.

The lack of sensitivity of the K_{Ic} measurement to microstructural features, as compared to the sensitivity of the CVN specimen and the tensile specimen is related to specimen design. K_{Ic} testing measures the initiation of fracture from an existing sharp crack, while a CVN specimen has a blunt notch and tensile reduction of area is measured on a smooth bar specimen. Propagation of a sharp crack under plain strain conditions in the K_{Ic} test is essentially controlled by stress. In a Charpy test or a tensile test, the conditions for fracture are dependent not only on the stress level but on the plastic strain that any element of material experiences. The presence of such items as sulphides, carbides and/or the presence of a weaker constituent such as bainite primarily lowers the critical strain at which ductile rupture proceeds. The sampling volume for fracture is also greater for the CVN and tensile tests because of the larger plastic zone involved.

Specimens oriented in the short transverse or thru-thickness direction showed reduced tensile ductility and Charpy V-notch toughness for all conditions tested. The anisotropy in this direction when compared with the longitudinal

and transverse direction is quite high. Generally the tensile ductility was reduced 66% while the Charpy V-notch toughness was reduced approximately 56%. The reduction of properties in the short transverse direction is primarily attributed to the textural characteristics created by the rolling process. Microstructural features are aligned in the direction of crack propagation. These features include inclusions (sulphides and oxides), and matrix microstructural features associated with chemical banding such as bainite bands.

Fracture surfaces of the steel were generally free of sulfide and oxide inclusions. This is consistent with metallographic examination of the steel. Although no quantitative analysis was carried out on the bulk inclusion content of the steel, standard metallographic examination together with SEM - EDXA analysis indicated that this steel was extremely "clean". Inclusions tended to be in small clusters and consisted primarily of alumina. In some cases, the alumina contained calcium as a minor constituent. Sulphides, when found, were associated with the alumina inclusions. Sulphides were never found on the fracture surfaces. Traces of Ti-CN and Nb-CN were found. Small rare earth inclusions were also found in the steel. Their presence is related to a proprietary complex deoxidizer used during the ESR melting process.

The mild notch tensile specimens provided the most sensitive evaluation of the effect of microstructure on properties. Charpy V-notch toughness exhibited much more sensitivity to microstructural effects than fracture toughness, K_{Ic}.

SUMMARY AND CONCLUSIONS

1. Increasing austenitizing temperature from 1550° F to 1750° F had little or no effect on the strength and toughness of Heat R3192 ESR melted 4340 steel

2. Decreasing the quench rate from 1000° F per minute to 500° F per minute had no effect on the strength and toughness.
3. Decreasing the quench rate from 500° F per minute to 100° F per minute had a significant effect on Charpy V-notch toughness. Lower Charpy V-notch toughness associated with the quench rate of 100° F per minute was due to the presence of bainite in the microstructure. The presence of bainite had a small effect on slow bend fracture toughness (K_{Ic}).
4. Plate anisotropy was very small in the plane of the plate (longitudinal versus transverse). Properties normal to the plane of the plate were affected drastically. Charpy V-notch toughness was decreased as much as 56% over the values obtained in the longitudinal (L-T) direction. Reduction in area of the mild notch tensile specimen was decreased as much as 64% in the thru-thickness direction when compared to the longitudinal (L) direction.
5. The cleanliness of the steel was very good. Inclusion clusters were primarily alumina with some calcium present. Small amounts of cerium oxides, titanium and niobium carbo-nitrides were present. Sulphides were extremely small and were associated with alumina or calcium aluminate inclusions. No elongated sulphide inclusions were found.
6. Fracture of both the standard tensile samples and the mild notch sample was by the development of a sharp neck and cup-cone failure. Initiation of fracture was at the center of the specimen.
7. In all the tests conducted, there was no evidence of anisotropic embrittlement of this material (i.e., intergranular fracture).

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Table 1

Composition of ESR

C	Mn	S	P	Si	Ni	Cr	Mo	V	Ti	Al	Cb	Co
0.43	0.67	0.002	0.011	0.12	1.65	0.76	0.24	0.059	0.003	0.020	0.007	0.012

Table 2

Heat Treating Conditions

	Austenitizing Temperature ($^{\circ}F$)	Quench Rate ($^{\circ}F$/Min.)	Tempering Temperature ($^{\circ}F$)	Hardness (HR_c)
15 A	1550	100	340	55
15 P	1550	500	360	54
15 W	1550	1000	390	56
16 A	1650	100	340	54
16 P	1650	500	360	55
16 W	1650	1000	390	55
17 A	1750	100	340	55
17 P	1750	500	360	55
17 W	1750	1000	390	55

TABLE [illegible]

MECHANICAL PROPERTIES

RESULTS OF TENSILE TESTS, CHARPY V-NOTCH TESTS,
HARDNESS TESTS AND FRACTURE TOUGHNESS BEND TESTS.

SPECIMEN CODE		YIELD STRENGTH (KSI)	TENSILE STRENGTH (KSI)	REDUCTION IN AREA (%)	ELONG. IN 1 IN (%)	HARDNESS HRc	CHARPY V - NOTCH ENERGY (FT. lbs.) TEMPERATURE 70F ***	-40F ***	FRACTURE TOUGHNESS Kq (ksi in^1/2)
15 A L		225	310	33.2	9.2	55	15.0	12.0	37.7 **
15 A T		204	291	30.6	9.0	54	12.3	9.3	
15 A S		97 *	126	40.0	7.3	56	8.0	6.3	
15 F L		234	308	39.0	10.6	53	18.7	16.3	41.3 ***
15 F T		235	310	44.0	12.5	55	18.3	16.3	
15 F S	NT								
15 W L		243	312	45.8	11.9	56	18.0	14.7	40.6 **
15 W T		251	317	41.1	10.4	56	18.7	14.3	
15 W S		117 *	155	21.8	4.4	56	8.0	5.7	
16 A L		201	293	32.4	11.5	52	12.0	9.3	38.1 ***
16 A T		212	301	35.6	10.5	55	13.7	10.5	
16 A S		112 *	141	43.5	7.5	55	7.7	5.7	
16 F L		236	308	47.8	12.0	55	19.0	15.6	40.8 **
16 F T		236	307	45.5	12.4	55	18.7	13.7	
16 F S	NT								
16 W L		243	309	42.6	10.4	55	19.0	12.7	40.5 ***
16 W T		[illegible]	311	44.3	12.1	56	17.3	13.3	
16 W S	NT								
17 A L		218	307	39.4	11.3	55	14.3	11.0	41.0 **
17 A T		215	310	37.8	11.5	55	15.3	10.7	
17 A S		116 *	140	50.6	9.9	55	8.0	6.3	
17 F L		[illegible]	309	46.3	11.9	55	16.3	12.7	42.9 ***
17 F T		241	307	46.0	11.9	56	18.3	12.7	
17 F S	NT								
17 W L		238	309	46.9	12.4	55	18.0	13.0	42.4 **
17 W T		236	307	43.0	11.8	55	[illegible]	[illegible]	
17 W S	NT								

* — WELD FAILURE
NT — NO TEST
** — AVERAGE OF TWO SPECIMENS
*** — AVERAGE OF THREE SPECIMENS

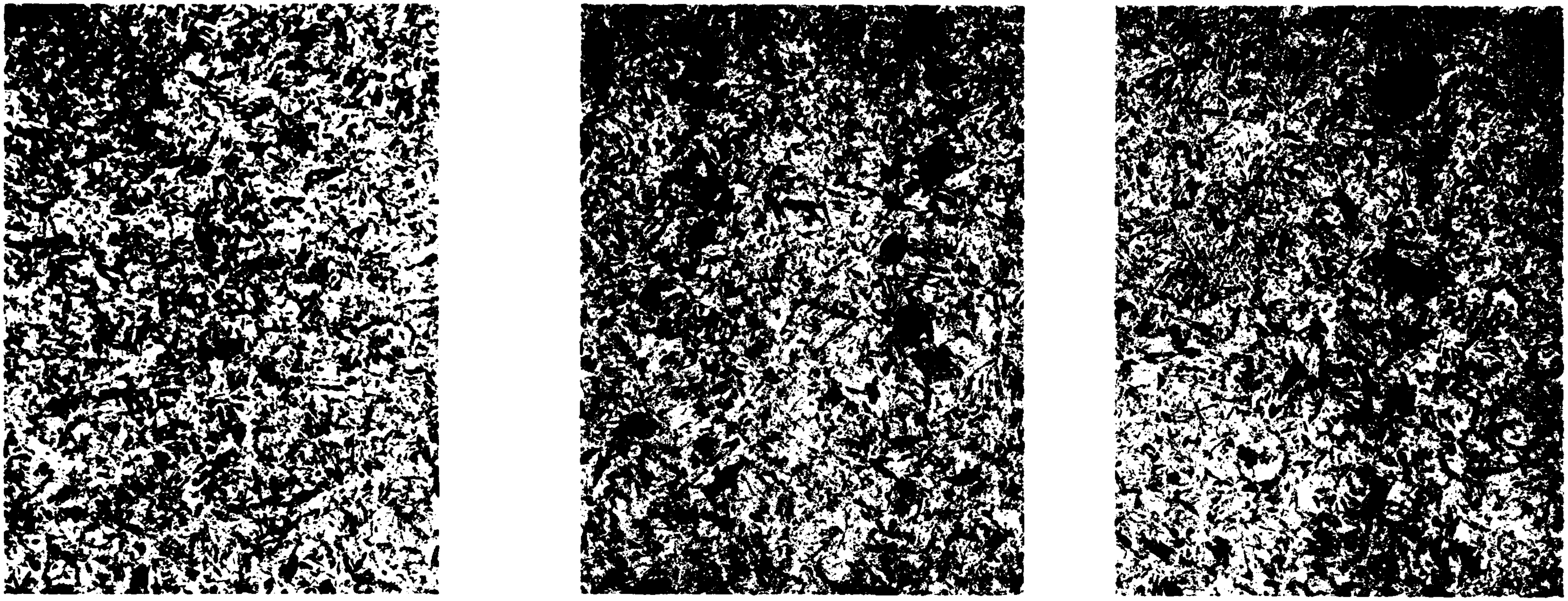
TABLE 4

NOTCH TENSILE TEST RESULTS

SPECIMEN CODE *		YIELD STRENGTH (KSI)	TENSILE STRENGTH (KSI)	REDUCTION IN AREA (%)
15 A L	**	256.1	340.9	28.3
15 A T	**	238.2	320.4	22.2
15 A S	**	207.9	340.4	9.8
15 P L	**	271.0	343.2	35.6
15 P T	**	264.9	339.8	35.2
15 W L	**	266.7	342.7	33.0
15 W T	**	271.0	351.3	34.1
15 W S	**	279.9	350.6	11.9
16 A L	**	230.9	320.4	23.4
16 A T	**	251.4	334.2	23.2
16 A S	**	238.0	335.5	11.5
16 P L	**	259.2	343.2	37.7
16 P T	**	257.8	340.1	35.8
16 W L	**	263.8	341.2	35.1
16 W T	**	267.0	347.9	32.5
17 A L	**	250.0	343.0	27.5
17 A T	**	230.0	345.9	25.2
17 A S	**	242.7	345.9	11.8
17 P L	**	259.5	341.2	36.2
17 P T	**	260.3	339.5	36.0
17 W L	**	269.9	341.1	37.3
17 W T	**	271.7	343.0	33.2

* NO TESTS FOR 15 P S, 16 P S, 16 W S, 17 P S AND 17 W S

** -- AVERAGE OF TWO TESTS

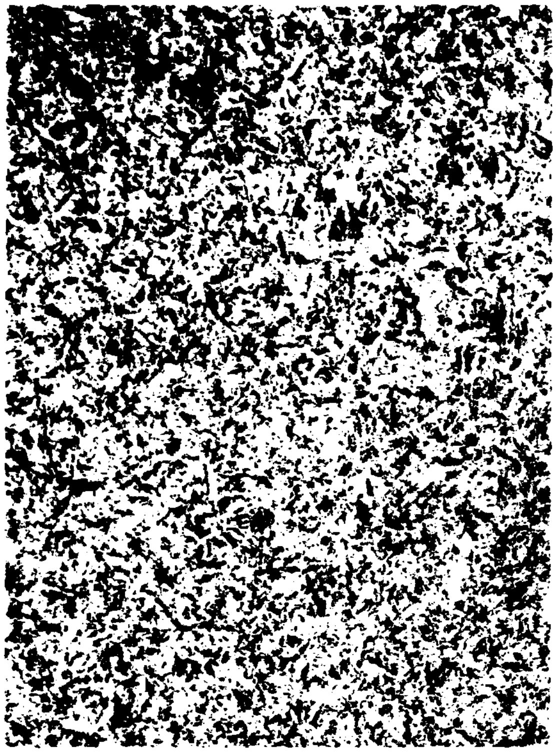


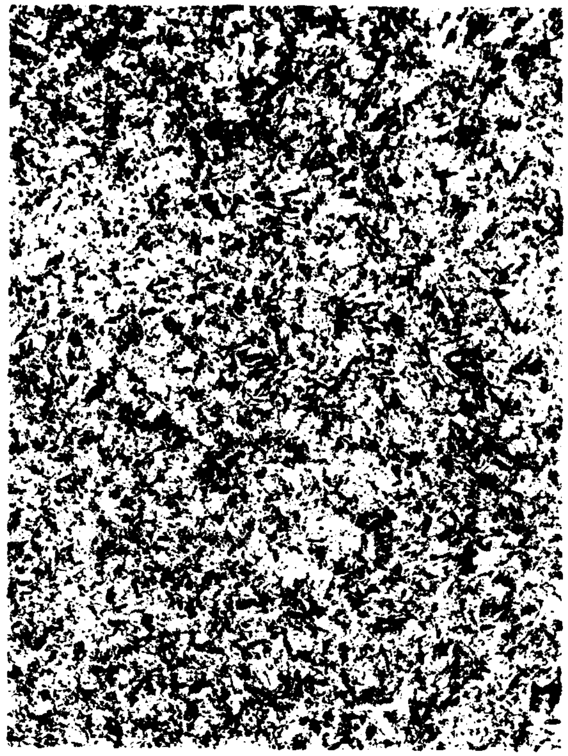
a) Austenitized 1500° F

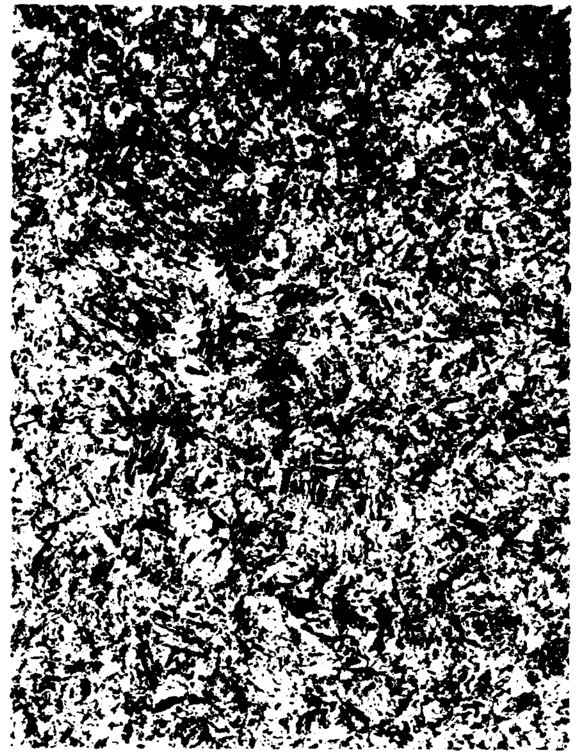
b) Austenitized 1650° F

c) Austenitized 1750° F

FIGURE 1: Microstructure of Samples Air Cooled at 100° F per Minute 500X





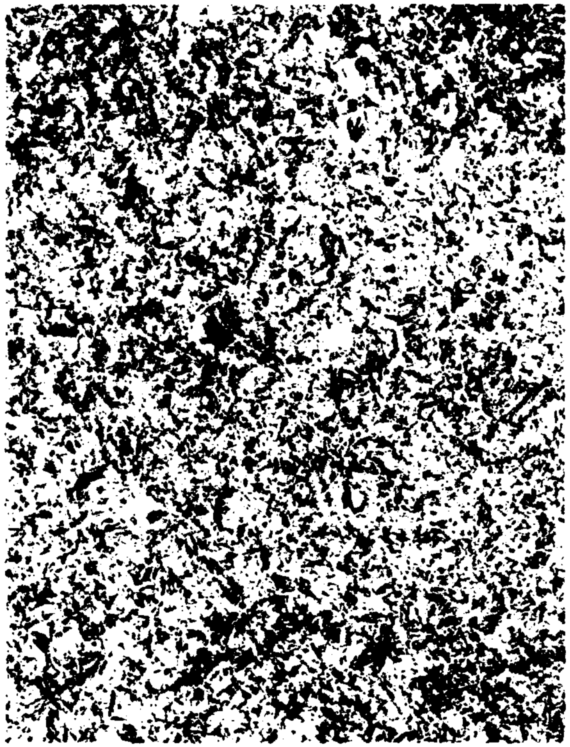


a) Austenitized 1550° F

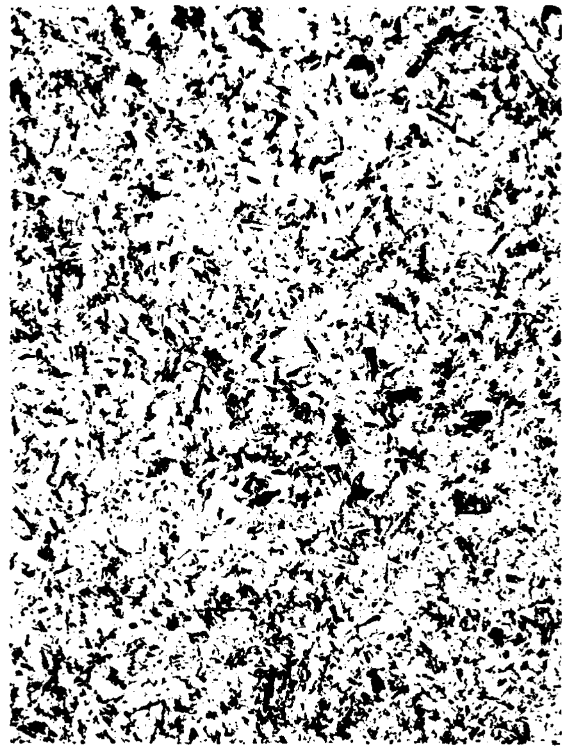
b) Austenitized 1650° F

c) Austenitized 1750° F

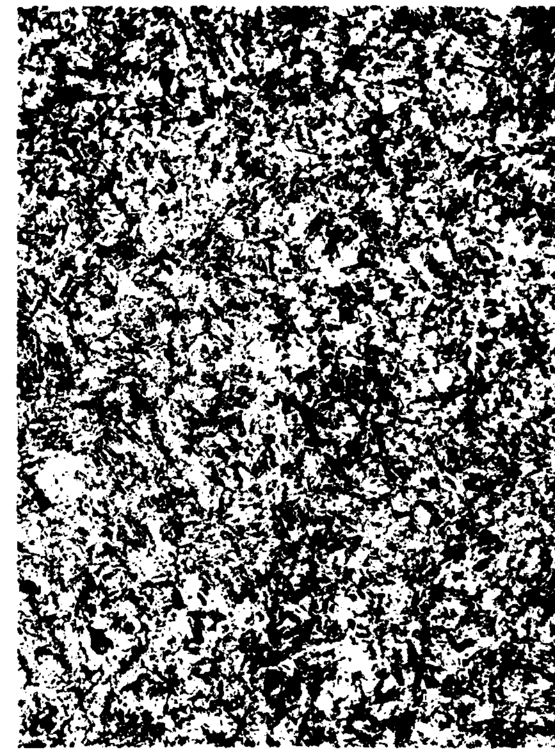
FIGURE 2: Microstructure of Samples Cooled at 500° F per Minute 500X



a) Austenitized 1550° F



b) Austenitized 1650° F



c) Austenitized 1750° F

FIGURE 3: Microstructure of Samples Cooled at 1000° F per Minute 500X

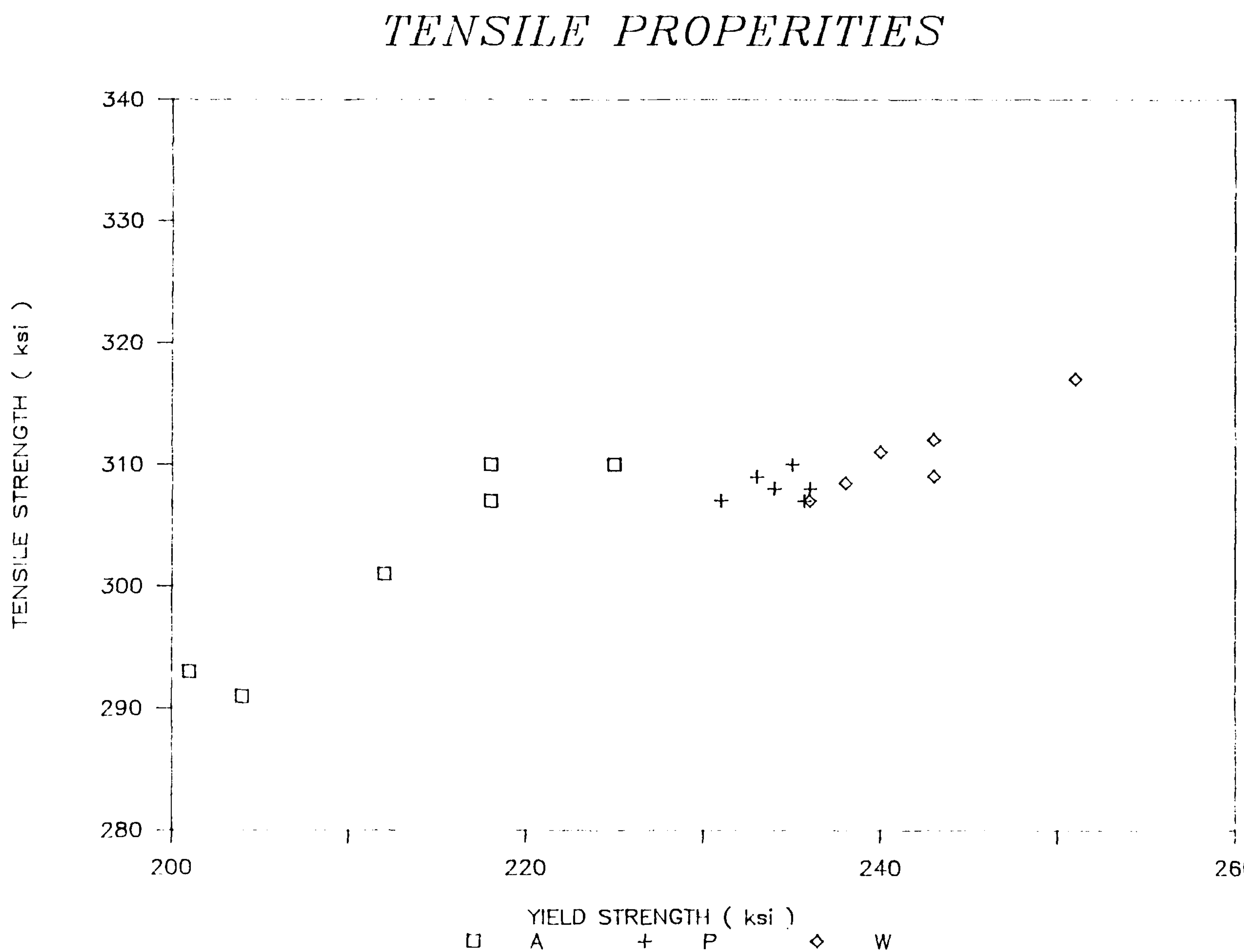


FIGURE 4: The Effect of Cooling Rate During Quenching on the Tensile Properties

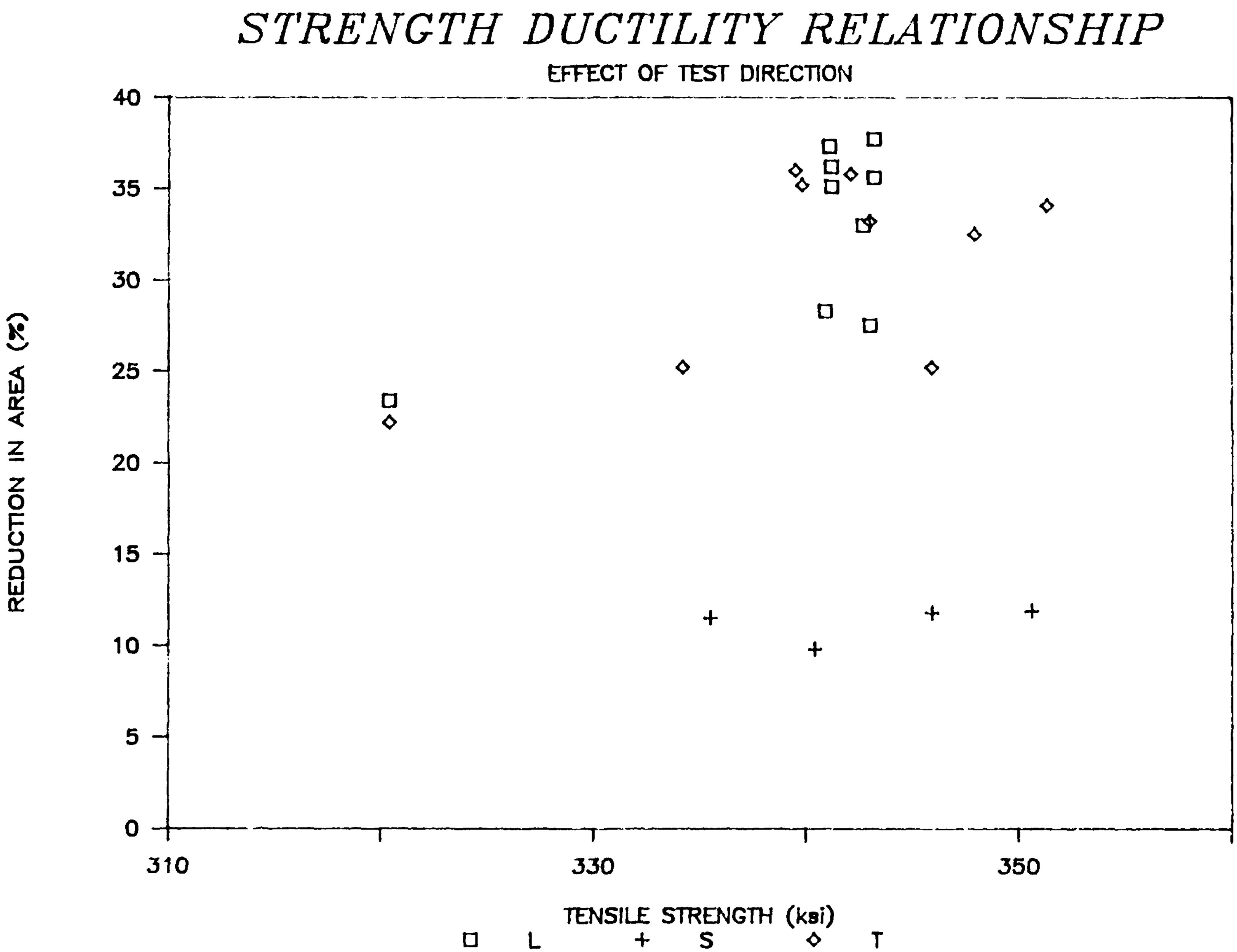


FIGURE 5: The Effect of Test Direction on the Strength-Ductility Relationship

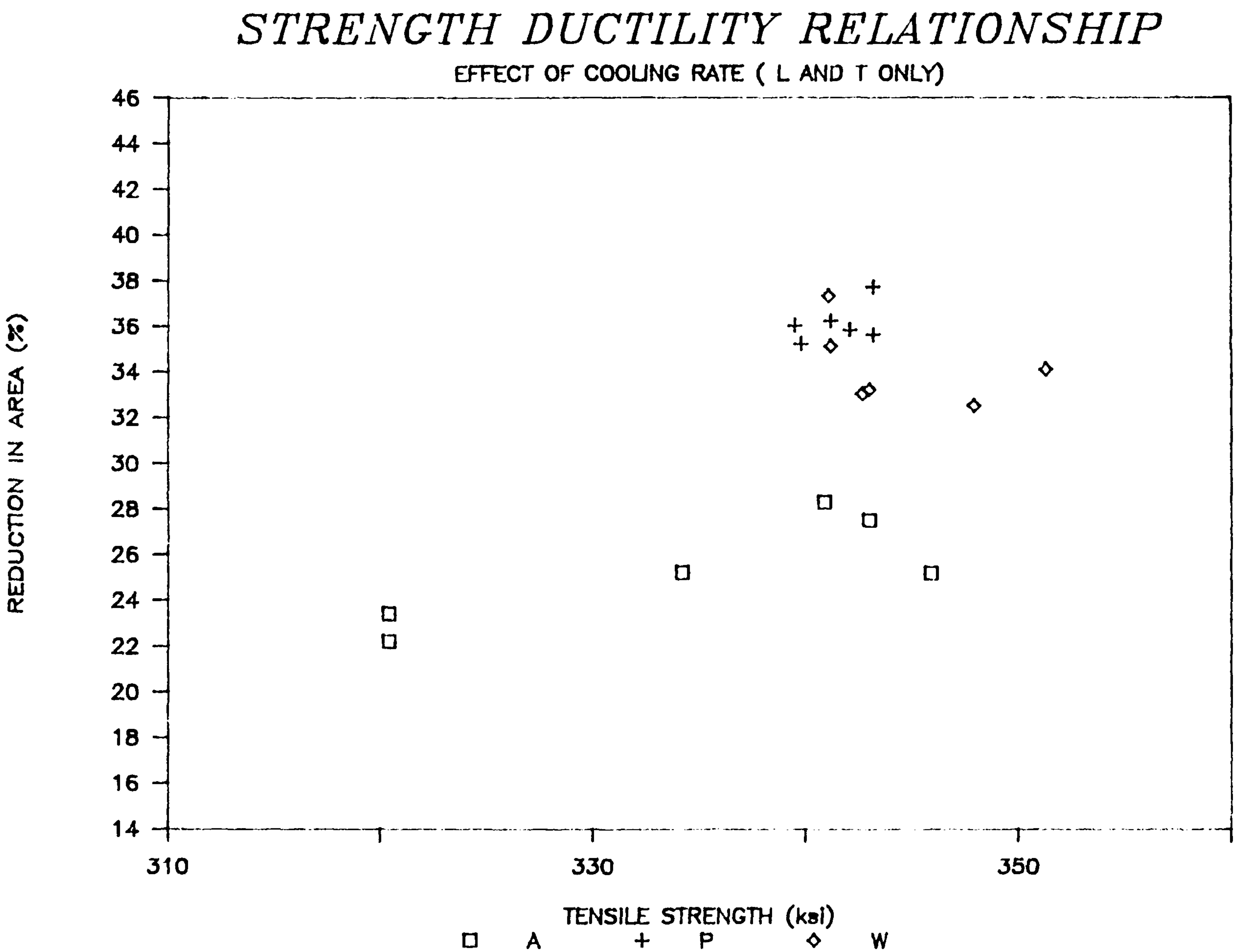


FIGURE 6: The Effect of Quench Rate on the Strength-Ductility Relationship for Notched Tensile Specimens Oriented in the L and T Directions

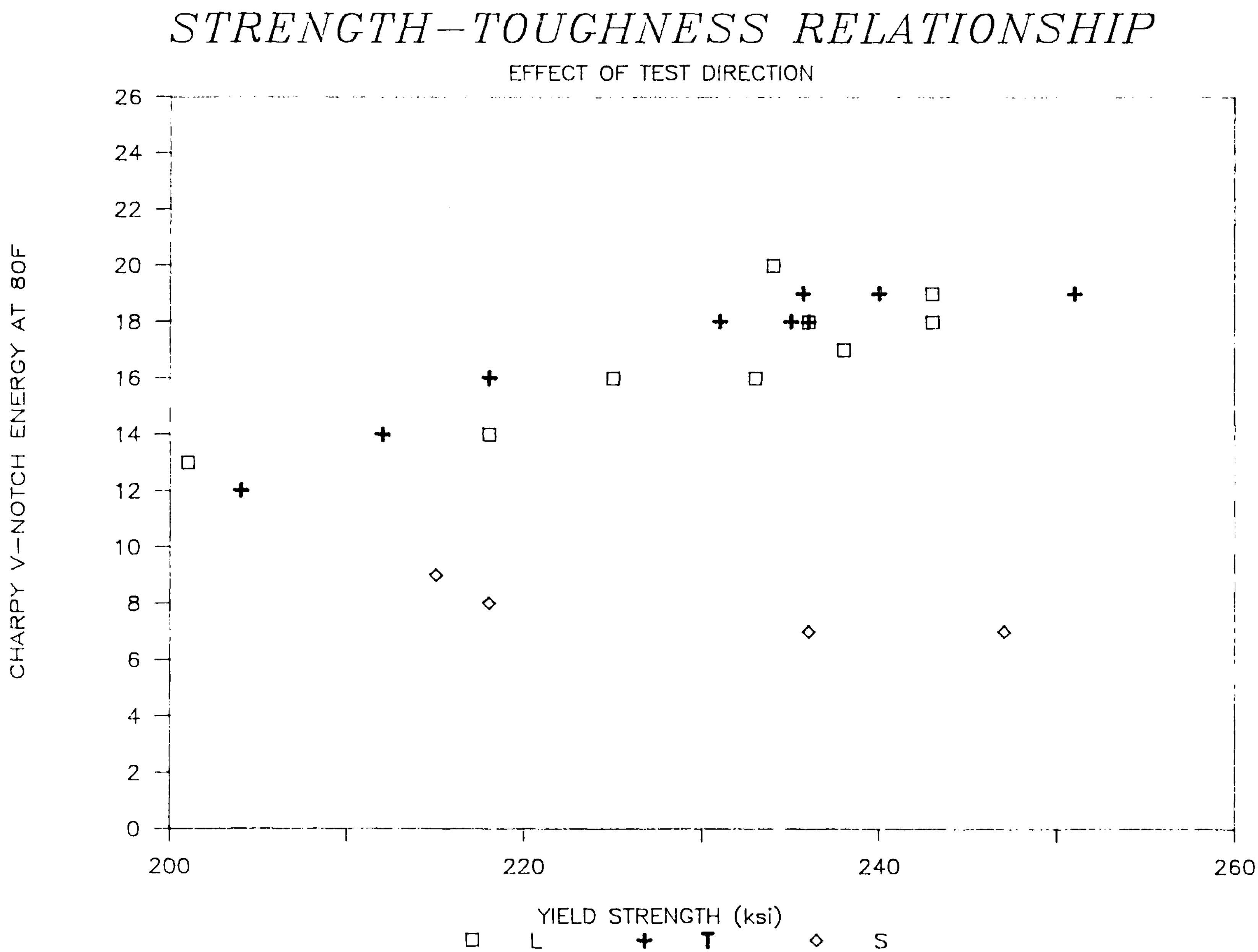


FIGURE 7: The Effect of Specimen Orientation on the Yield Strength, Charpy V-Notch Toughness Relationship at 80° F

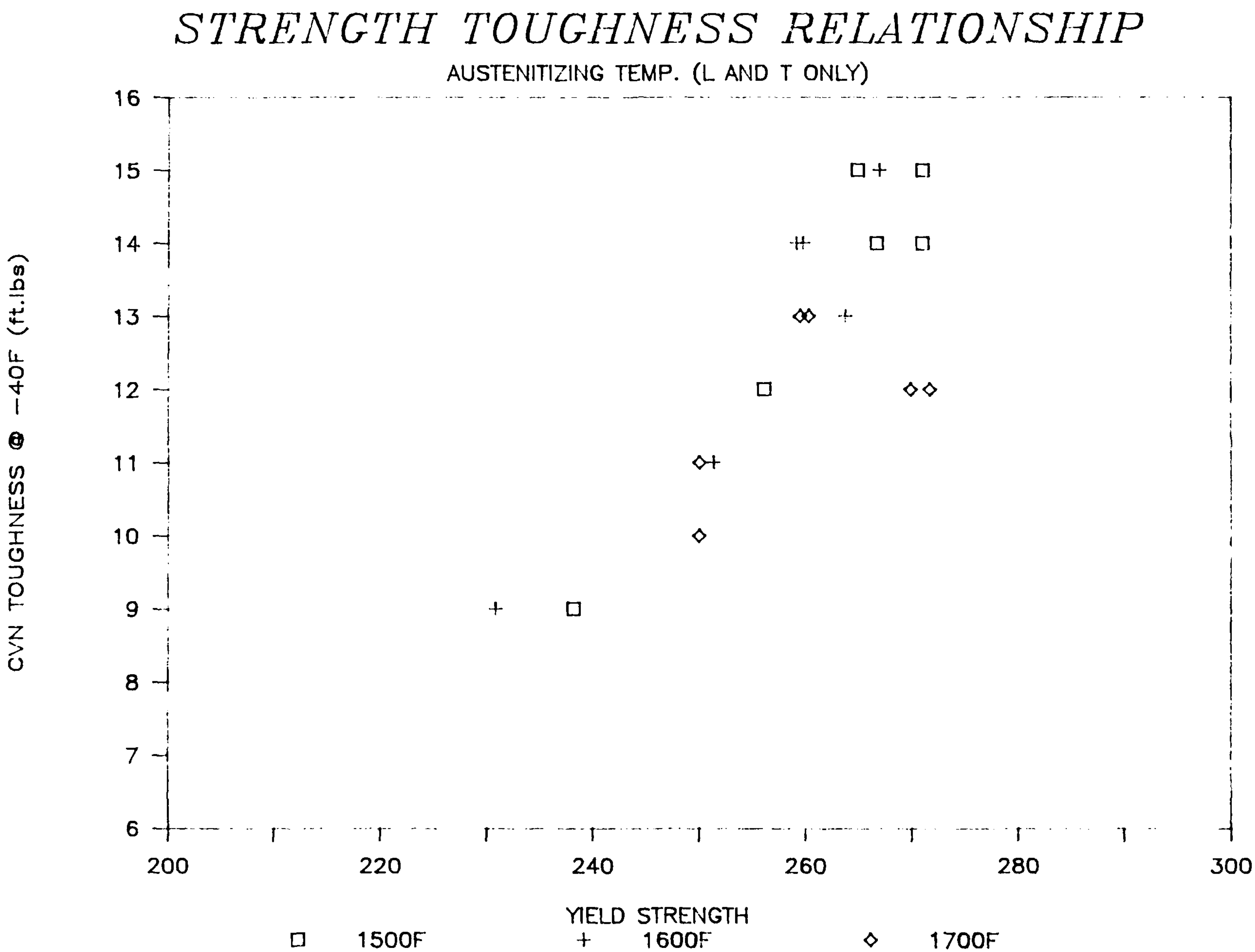


FIGURE 8: The Effect of Austenitizing Temperature on the Yield Strength, Charpy V-Notch Toughness Relationship at -40° F

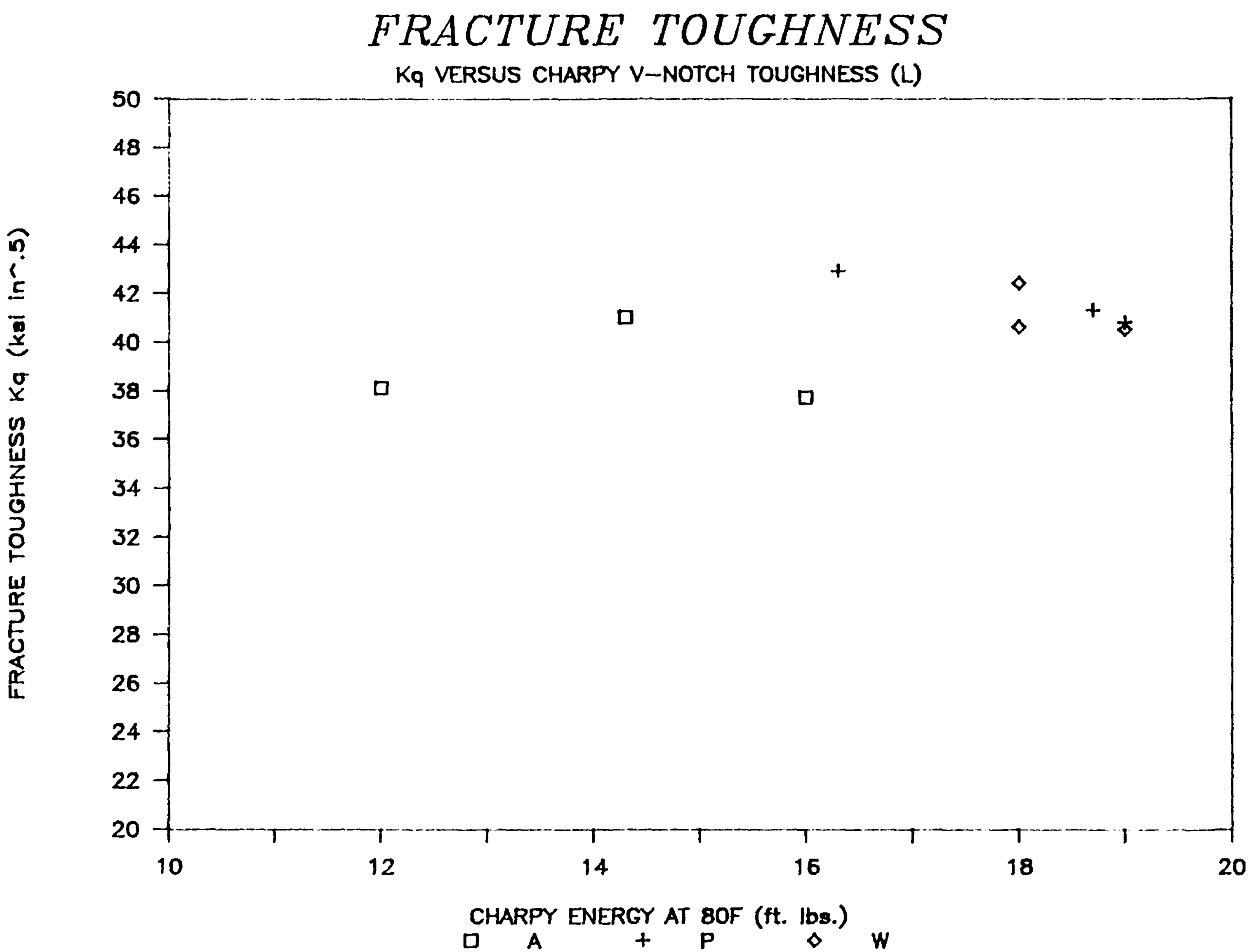
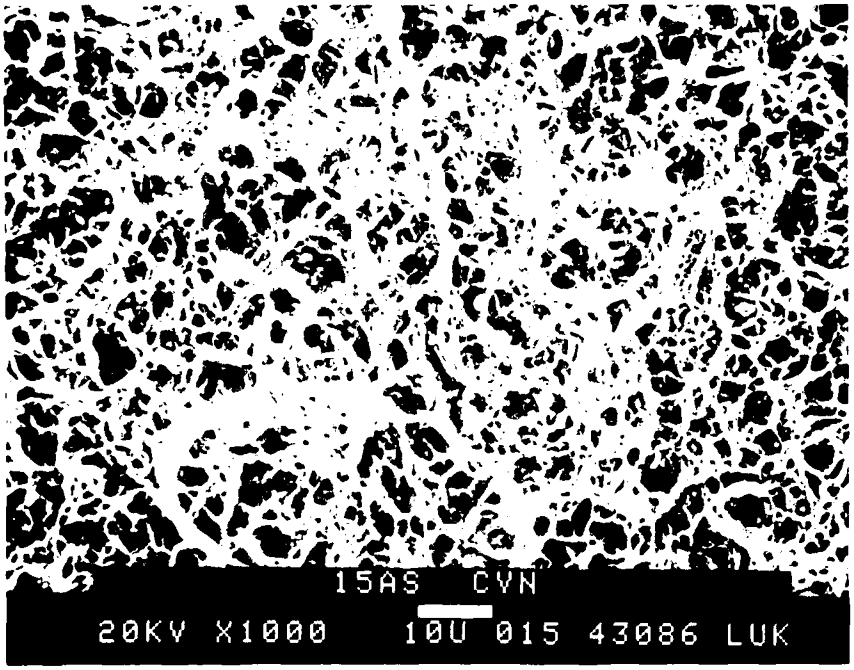


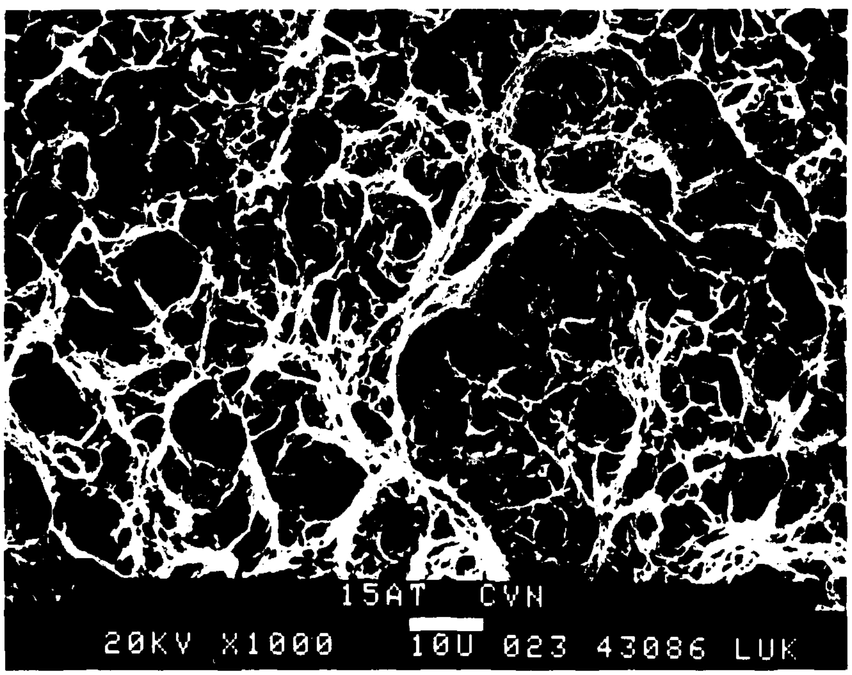
FIGURE 9: Relationship Between Kq and Charpy V-Notch Energy at 80° F



a) Sample 15AS

Orientation S

1000X

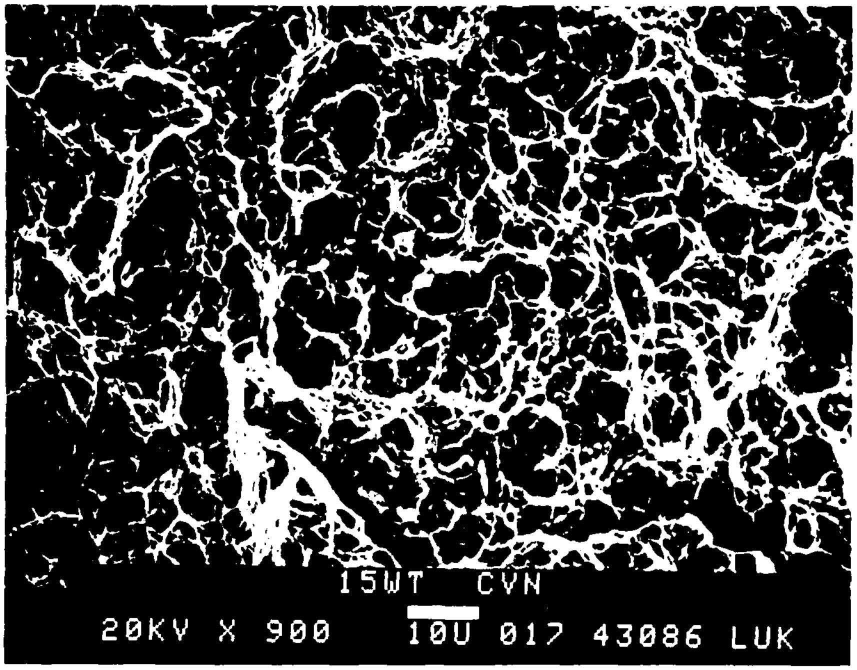


b) Sample 15AT

Orientation TL

1000X

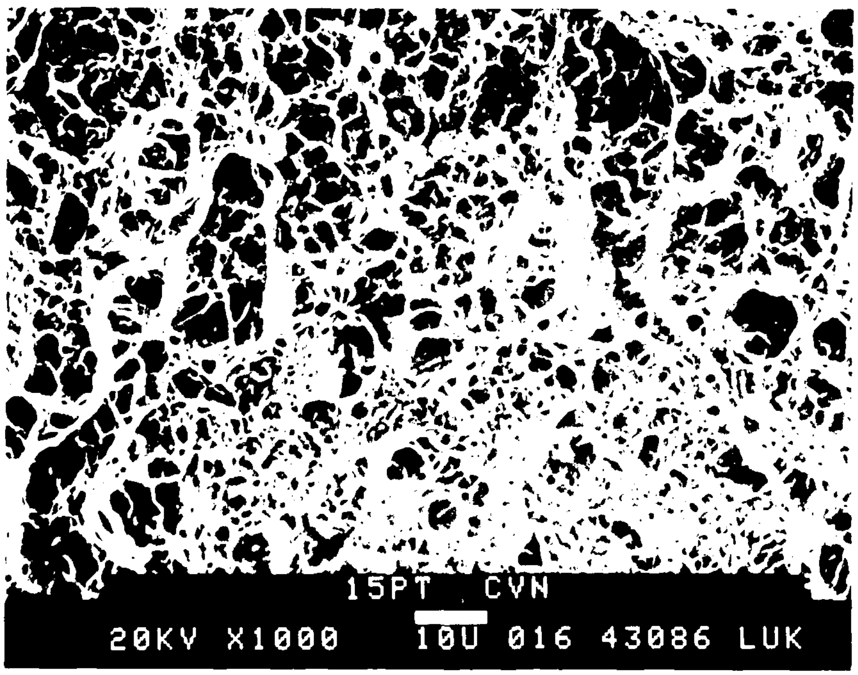
FIGURE 10: Charpy V-Notch SEM Fractograph of Slow Cooled Samples Austenitized at 1500° F



a) Sample 15WT

Orientation TL

900X

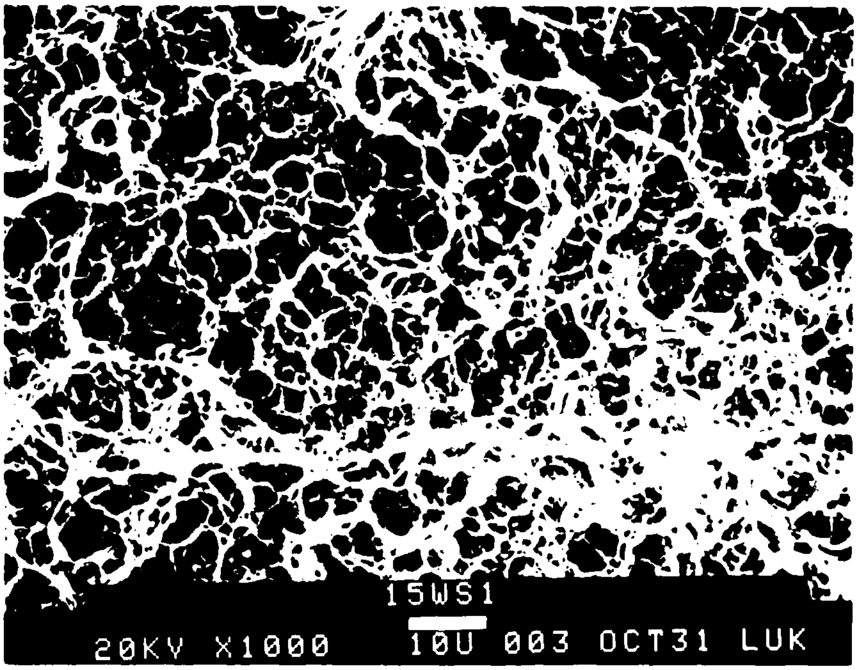


b) Sample 15PT

Orientation TL

1000X

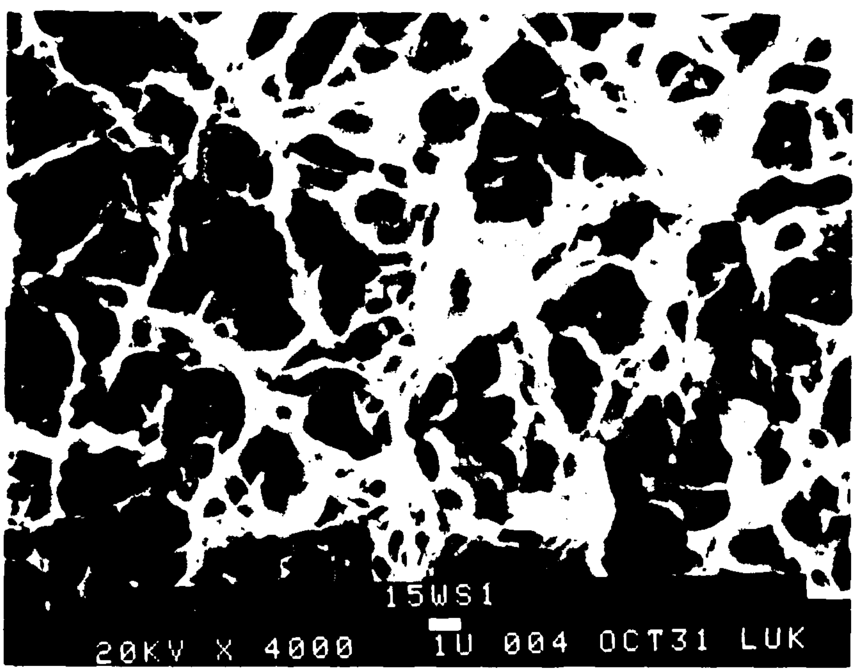
FIGURE 11: Charpy V-Notch SEM Fractograph of Slow Cooled Sample Austenitized at 1550° F



a) Sample 15WS

Orientation S

1000X

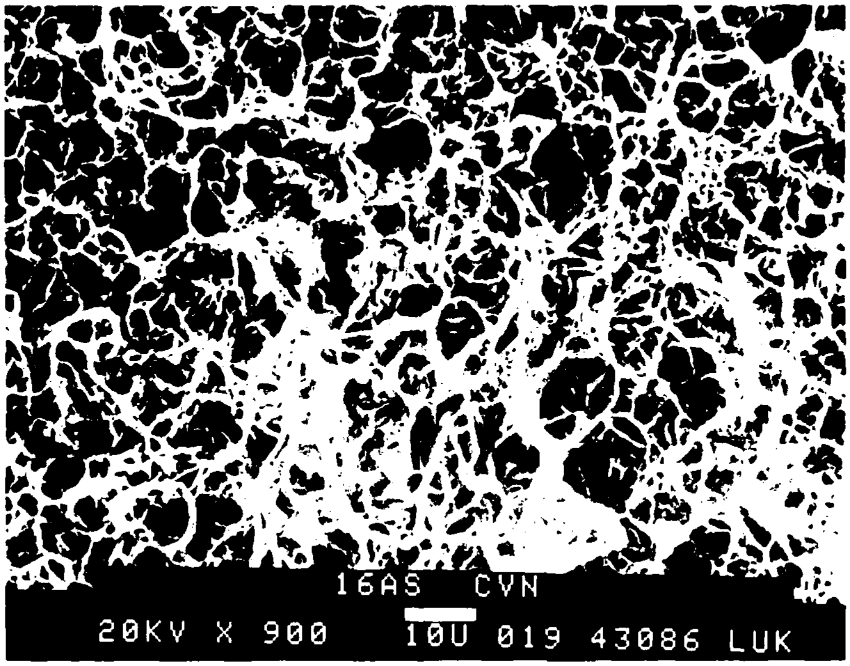


b) Sample WS

Orientation S

4000X

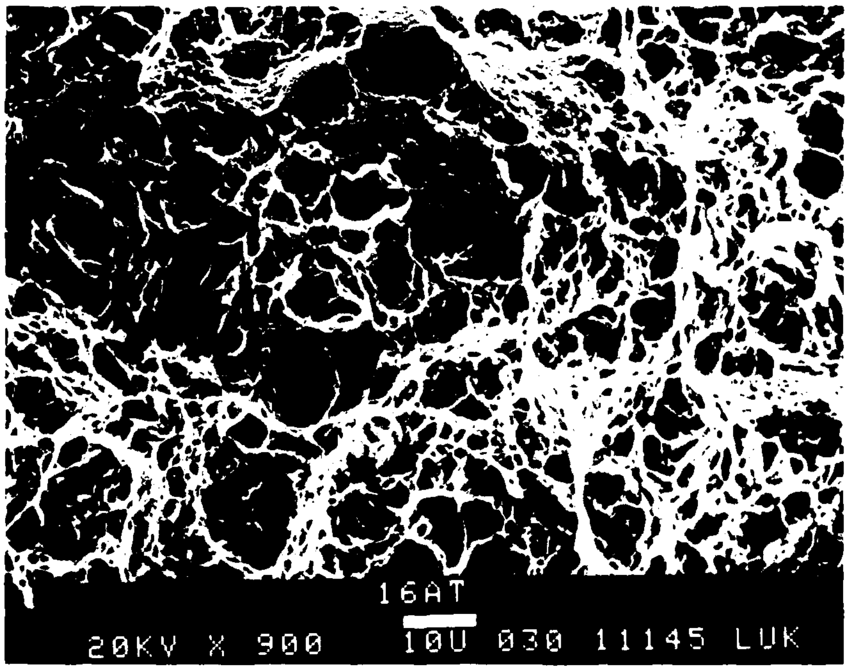
FIGURE 12: Charpy V-Notch SEM Fractograph of Slow Cooled Sample Austenitized at 1550° F



a) Sample 16AS

Orientation S

900X

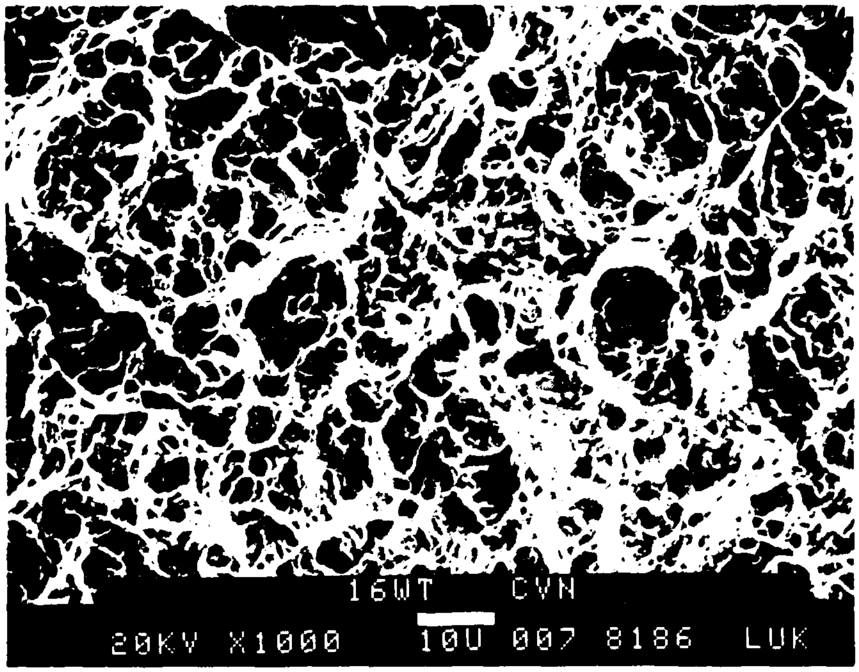


b) Sample 16AT

Orientation TL

900X

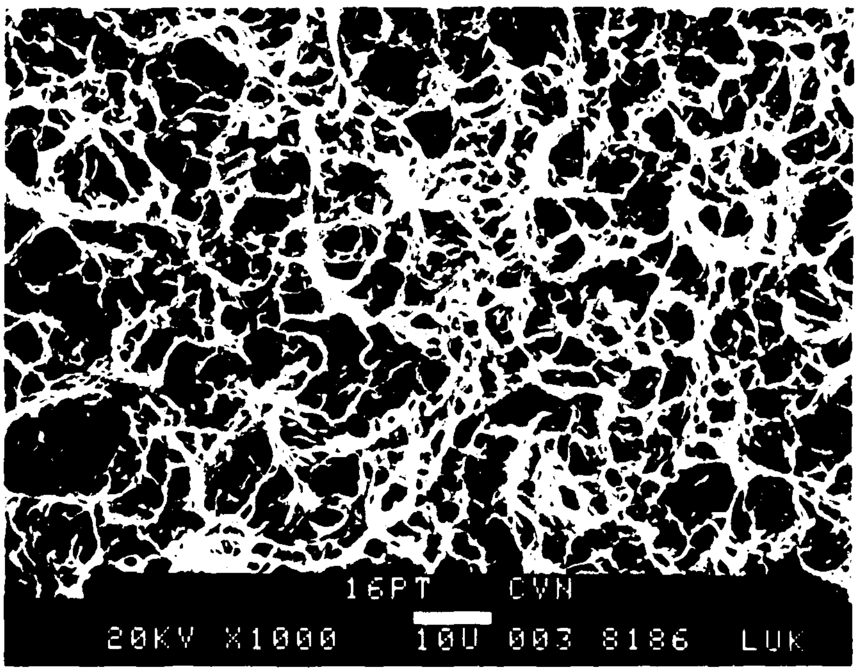
FIGURE 13: Charpy V-Notch SEM Fractograph of Slow Cooled Sample Austenitized at 1650° F



a) Sample 16WT

Orientation TL

1000X

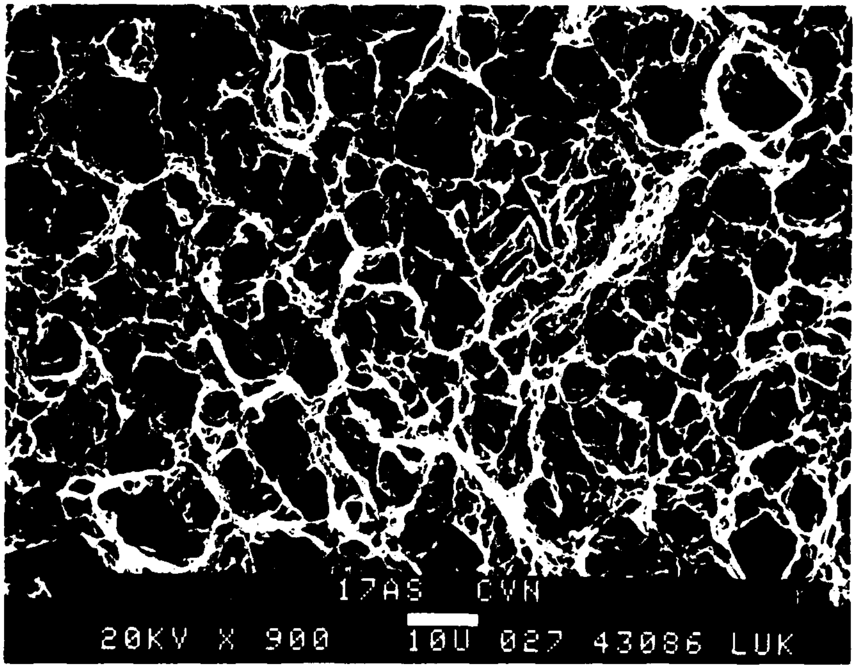


b) Sample 16PT

Orientation TL

1000X

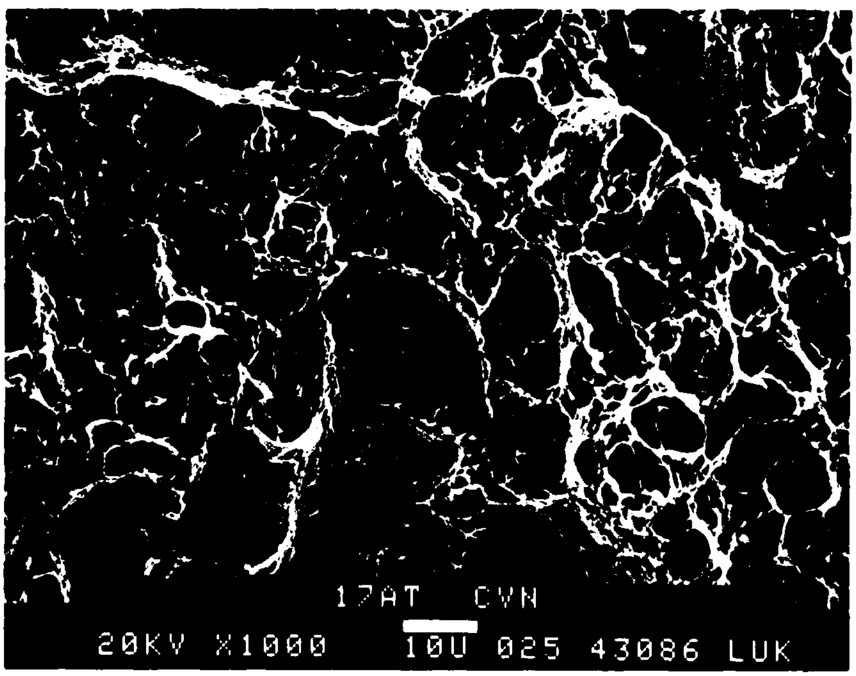
FIGURE 14: Charpy V-Notch SEM Fractograph of Samples Cooled at 500° F per Minute (P) and at 1000° F per Minute (W) Austenitized at 1650° F



a) Sample 17AS

Orientation S

900X

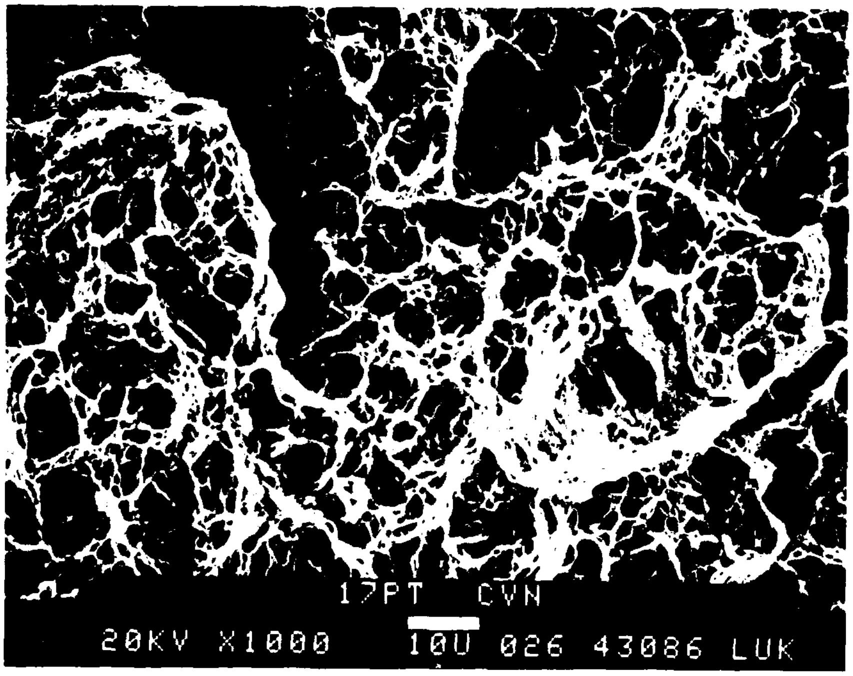


b) Sample 17AT

Orientation TL

1000X

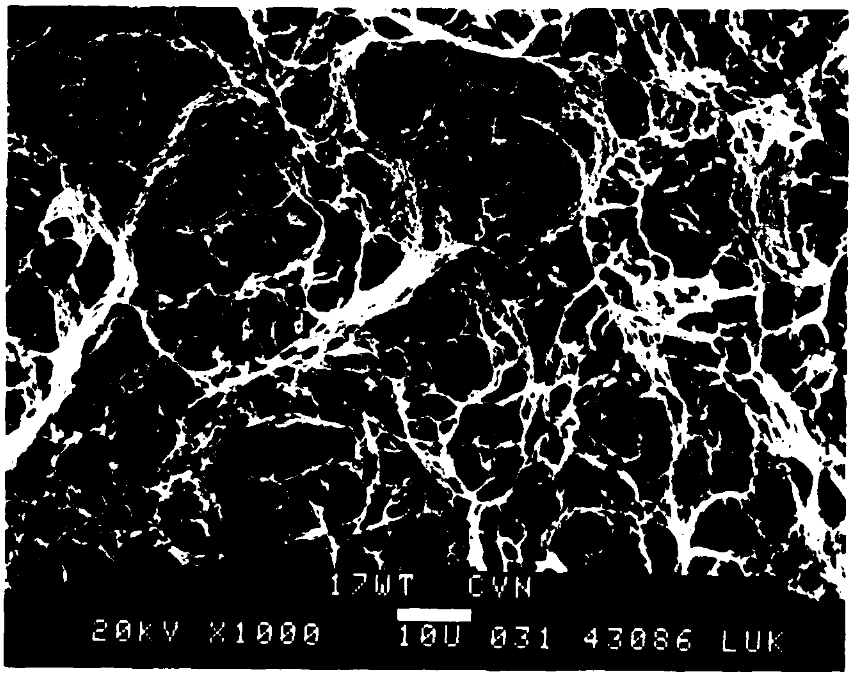
FIGURE 15: Charpy V-Notch SEM Fractograph of Samples Austenitized at 1750° F and Quenched at 100° F per Minute



a) Sample 17PT

Orientation TL

1000X

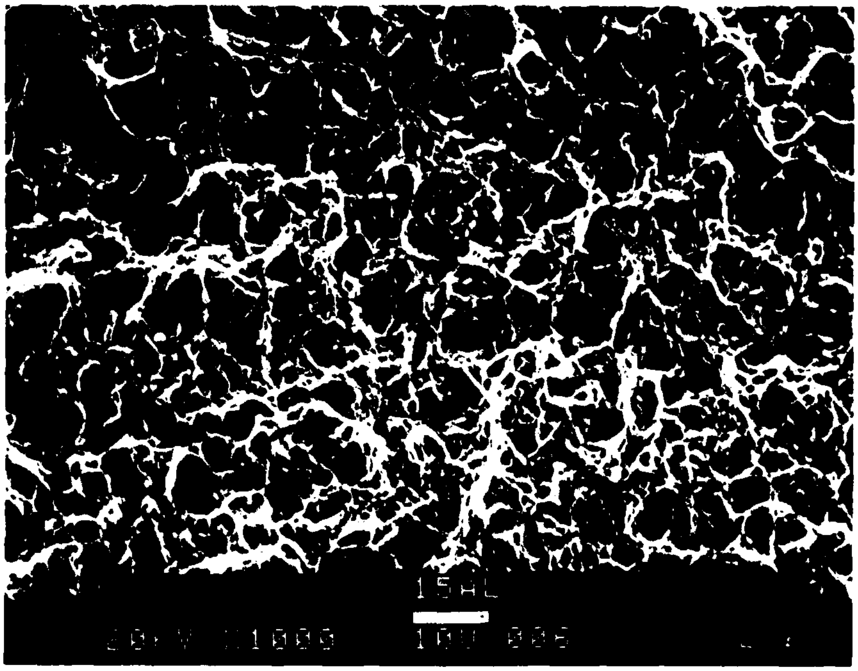


b) Sample 17WT

Orientation TL

1000X

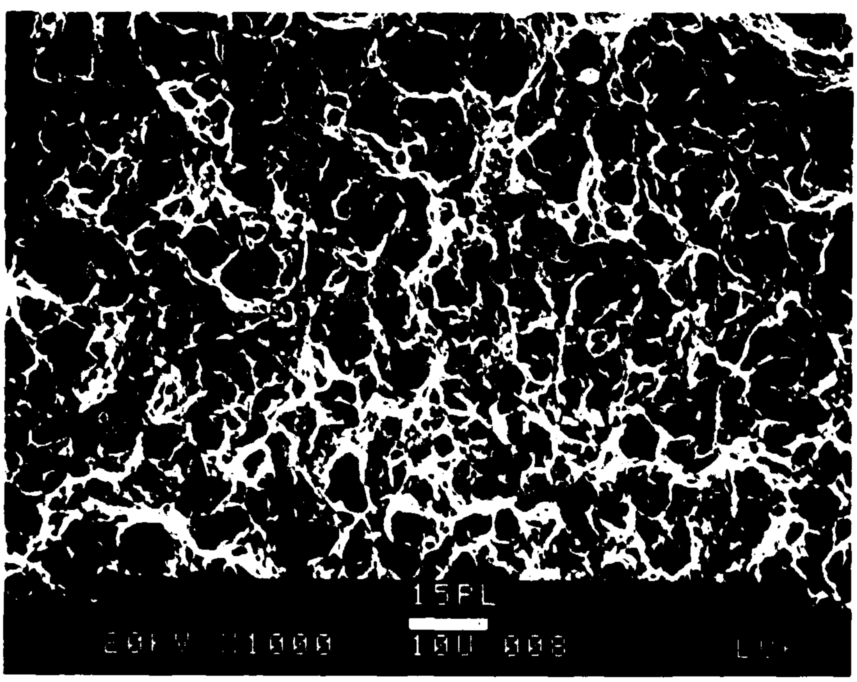
FIGURE 16: SEM Fractograph of Charpy V-Notch Samples Austenitized at 1750° F and Quenched 500° F per Minute (Fig. 16a) and Water Quenched (Fig. 16b)



a) Sample 15AL

Orientation LT

1000X

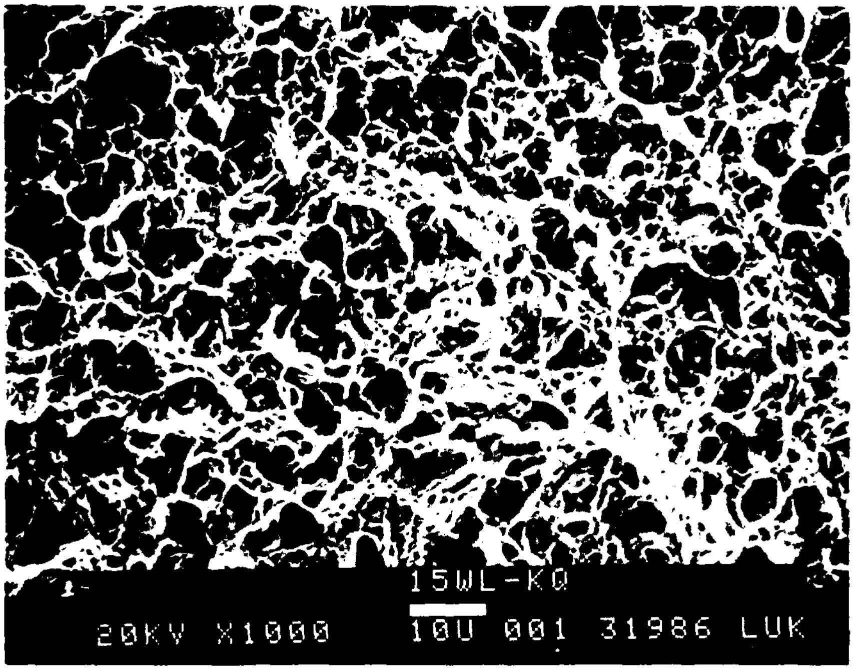


b) Sample 15PL

Orientation LT

1000X

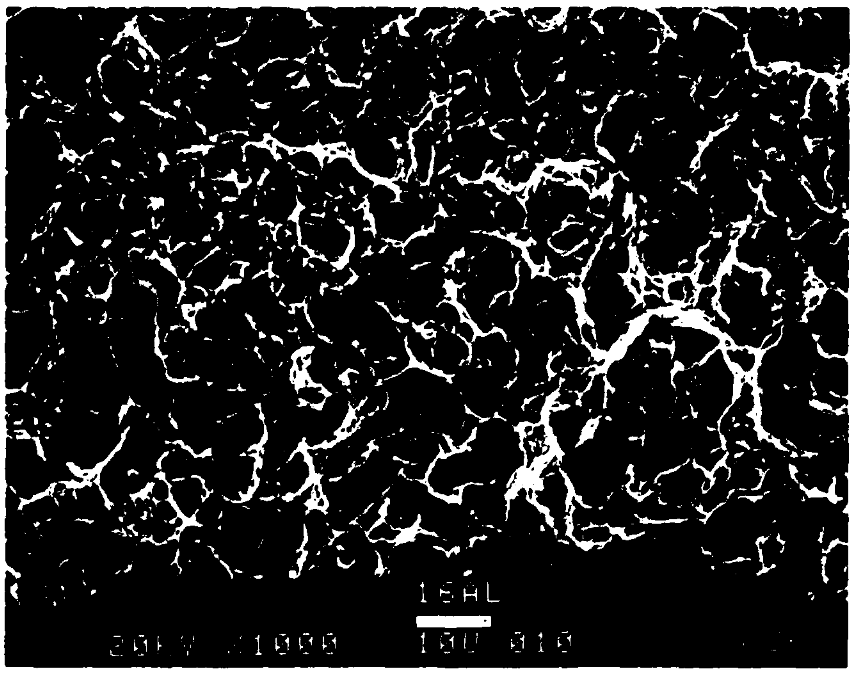
FIGURE 17: SEM Fractograph of Slow Bend Fracture Toughness Specimen Austenitized at 1500° F



a) Sample 15WL

Orientation LT

1000X

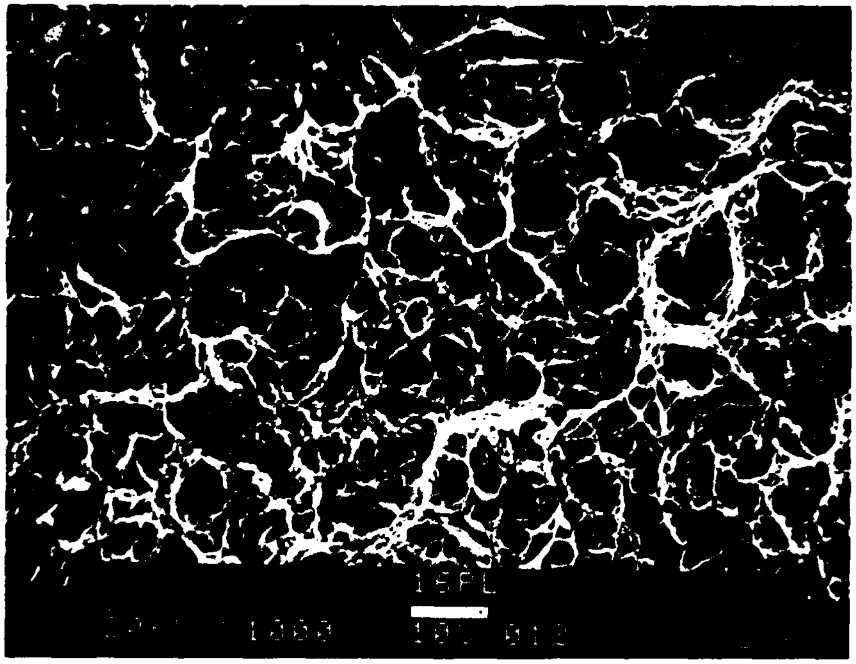


b) Sample 16AL

Orientation LT

1000X

FIGURE 18: SEM Fractograph of Slow Bend Fracture Toughness Specimen Austenitized at 1550° F (Fig. 18a) and 1650° F (Fig. 18b)

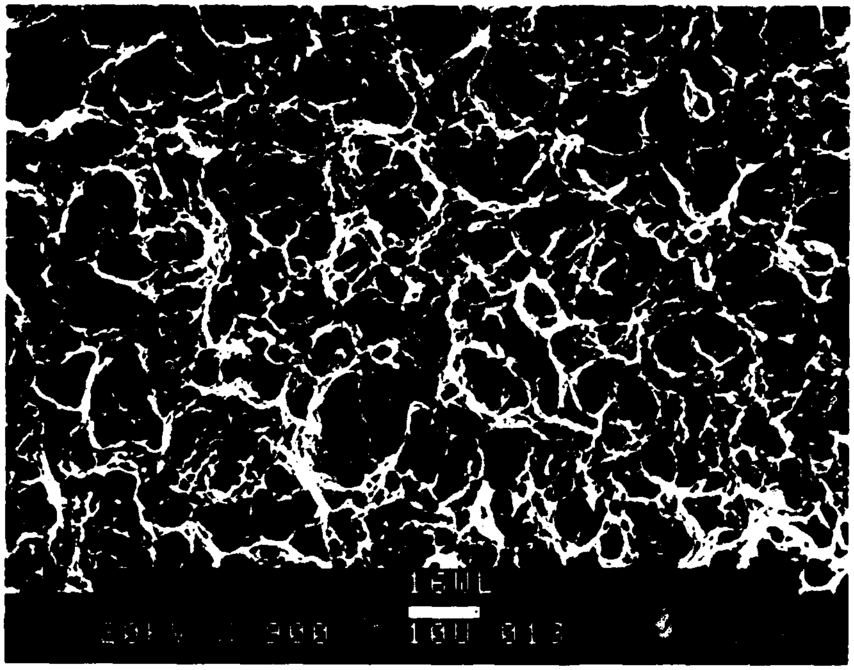


a) Sample 16PL

Orientation LT

Austenitized 1650° F

Quenched 500° F/Min.



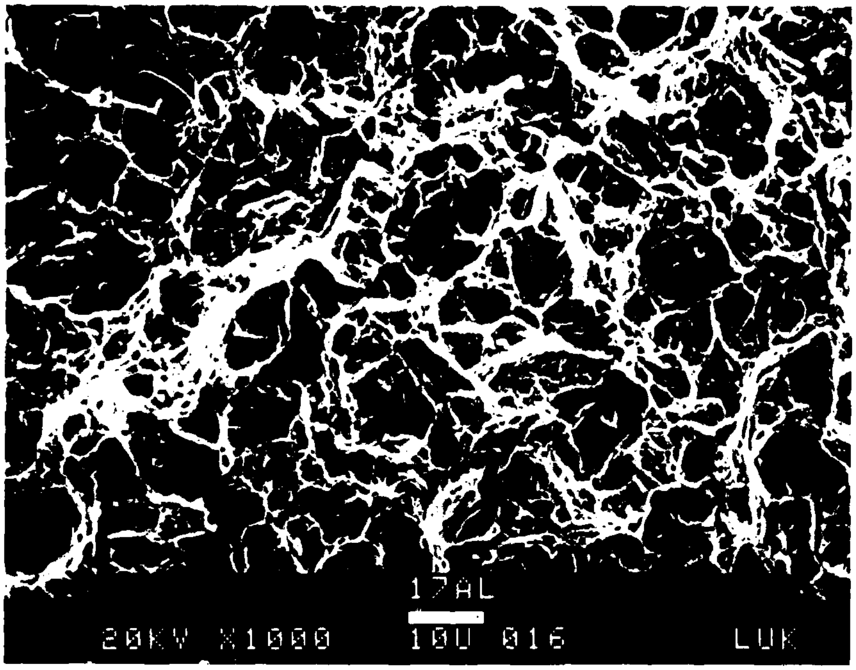
b) Sample 16WL

Orientation LT

Austenitized 1650° F

Quenched 500° F/Min.

FIGURE 19: SEM Fractograph of Slow Bend Fracture Toughness Specimen Austenitized at 1650° F

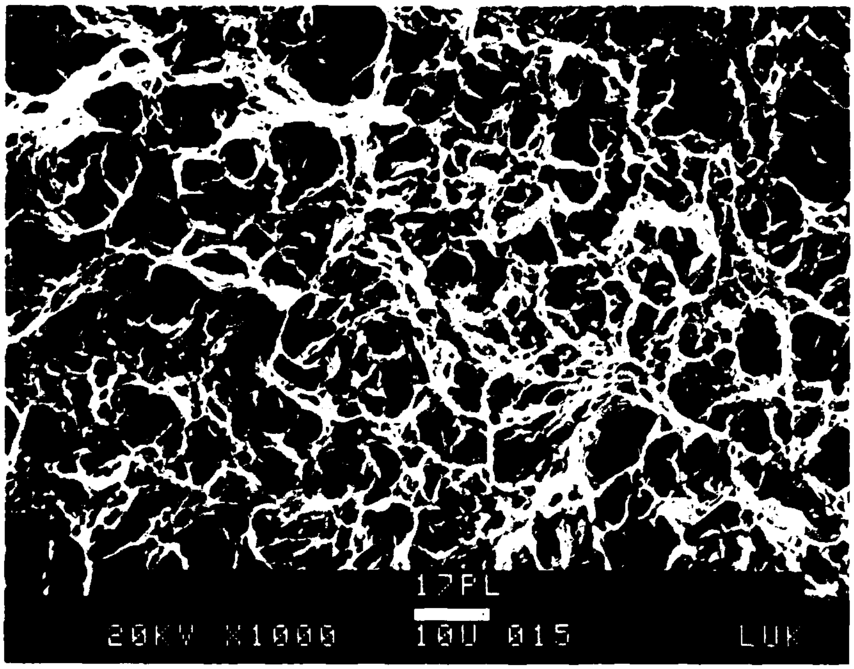


a) Sample 17AL

Orientation LT

Austenitized 1750° F

Quenched 100° F/Min.



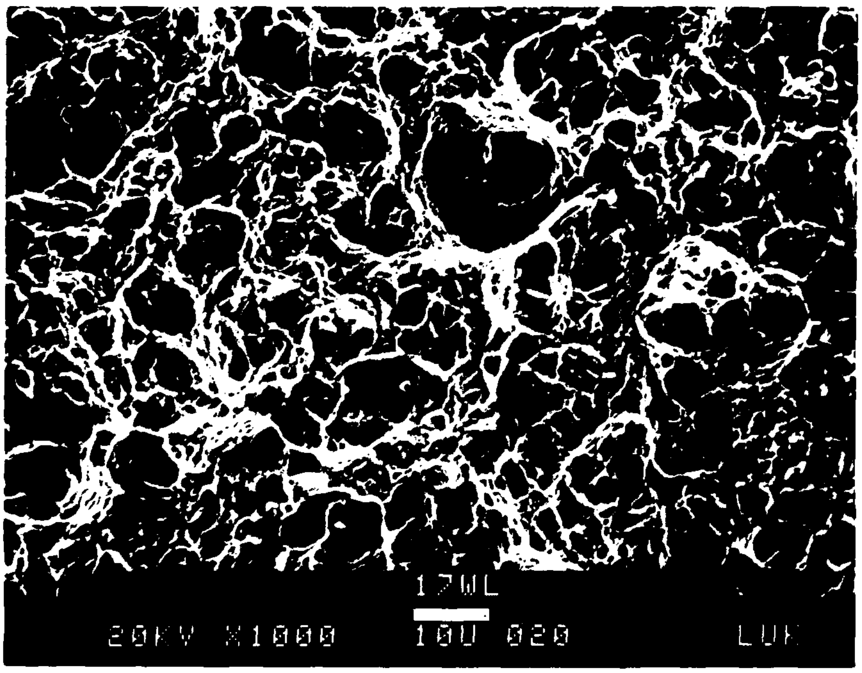
b) Sample 17PL

Orientation LT

Austenitized 1750° F

Quenched 500° F/Min.

FIGURE 20: SEM Fractograph of Slow Bend Fracture Toughness Specimen Austenitized at 1750° F



a) Sample 17WL

Orientation LT

Austenitized 1750° F

Quenched 1000° F/Min.

FIGURE 21: SEM Fractograph of Slow Bend Fracture Toughness Specimen Austenitized at 1750° F

a) Sample 16W

Orientation S

400X

b) Sample 16W

Orientation S

2600X

FIGURE 22: Inclusions Viewed on A Plane Normal to Thru Thickness Direction

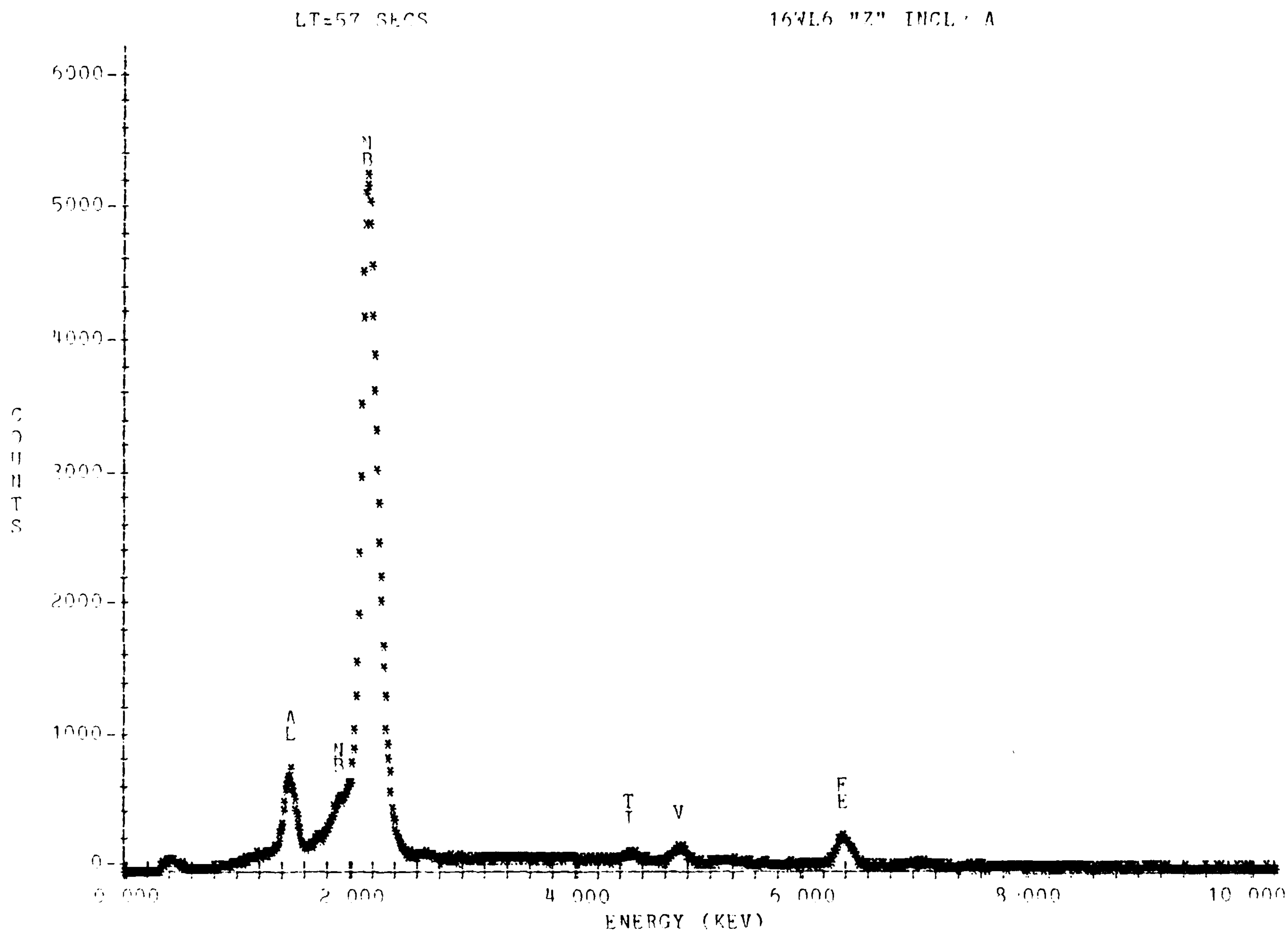


FIGURE 23: EDX-A Spectra of Inclusion "A" in Figure 22b

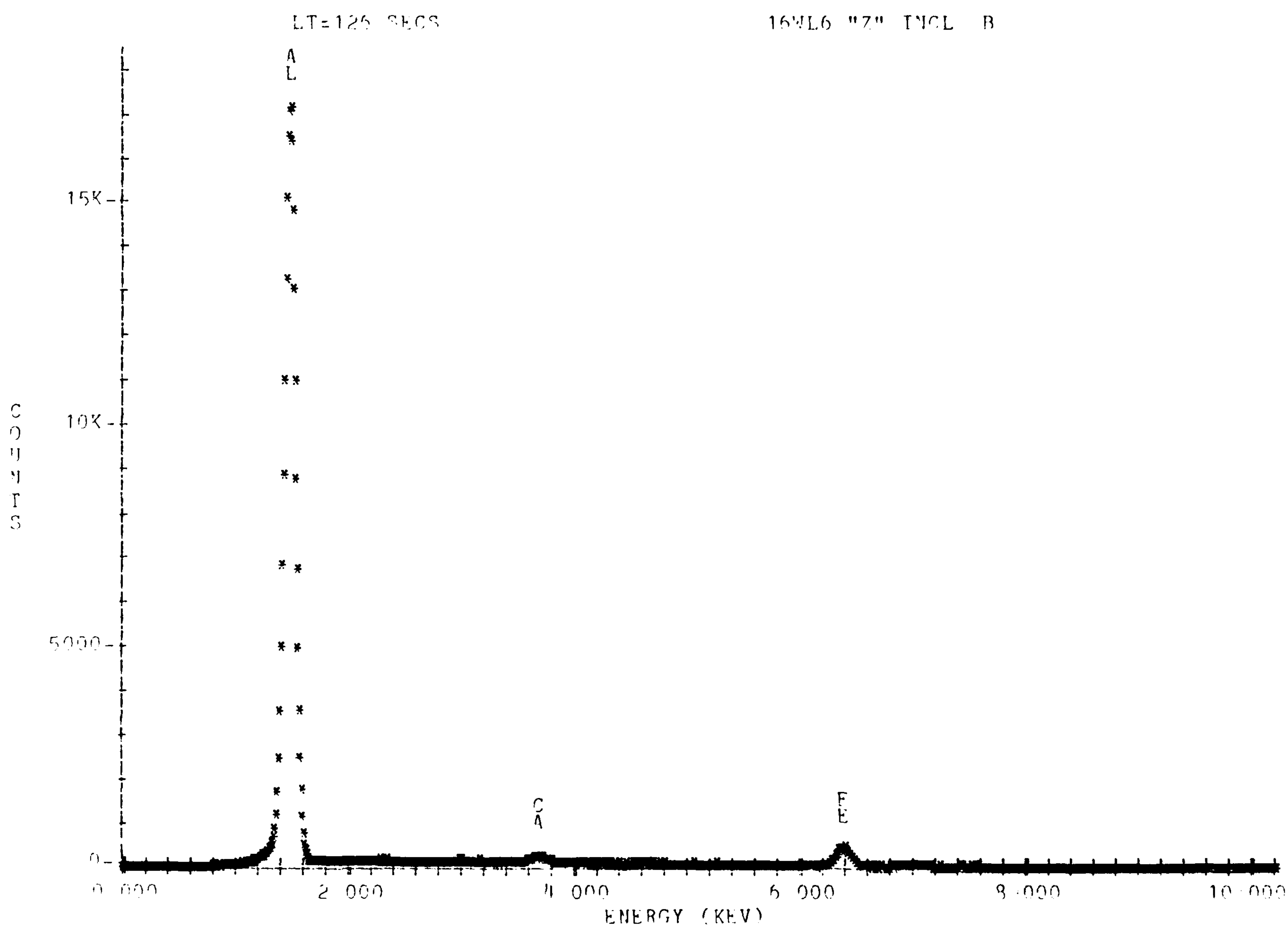
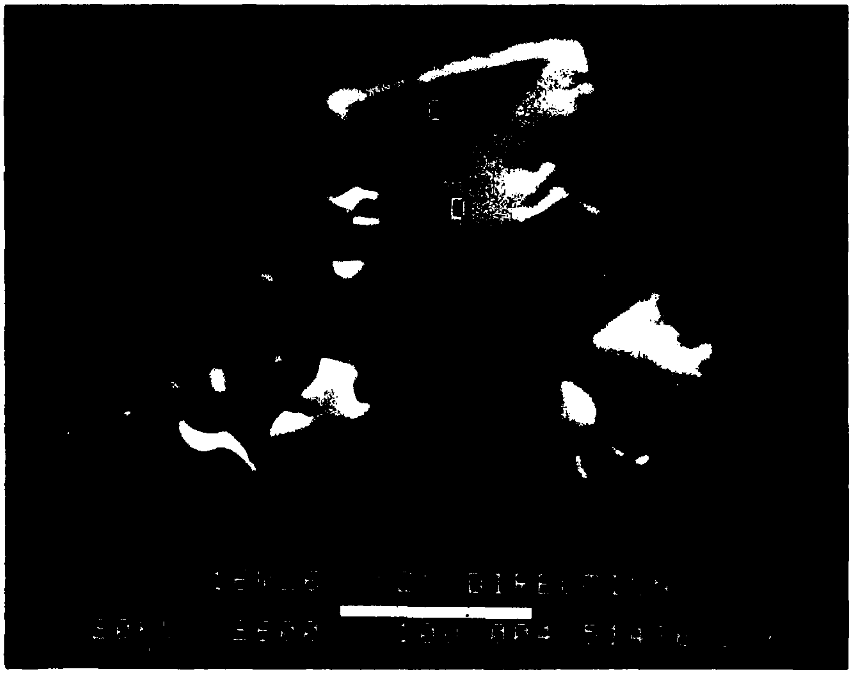


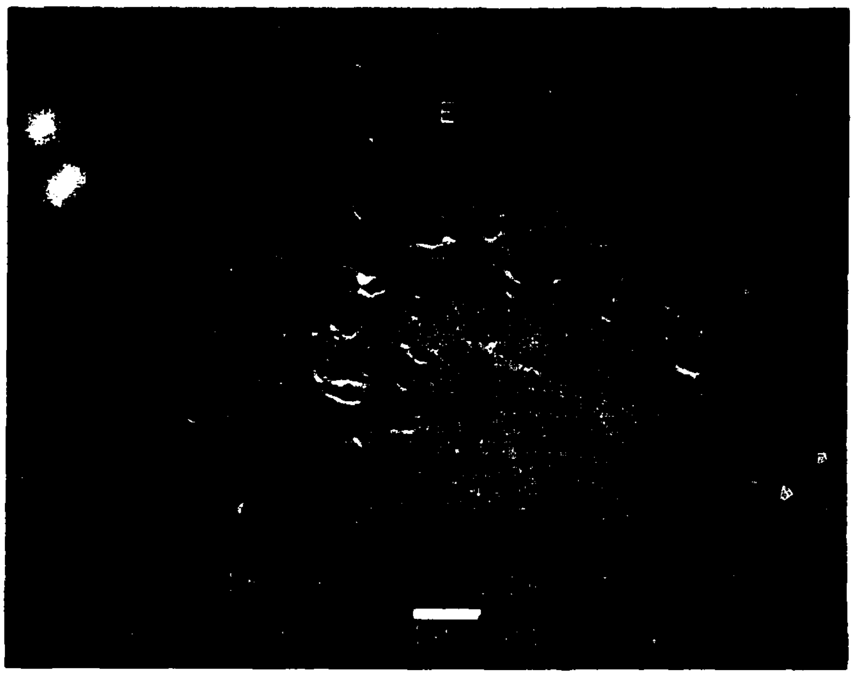
FIGURE 24: EDX-A Spectra from Inclusion "B" in Figure 22b



a) Sample 16W

Orientation S

2600X



b) Sample 16W

Orientation S

900X

FIGURE 25: Inclusions Viewed on A Plane Normal to The Thru Thickness Direction

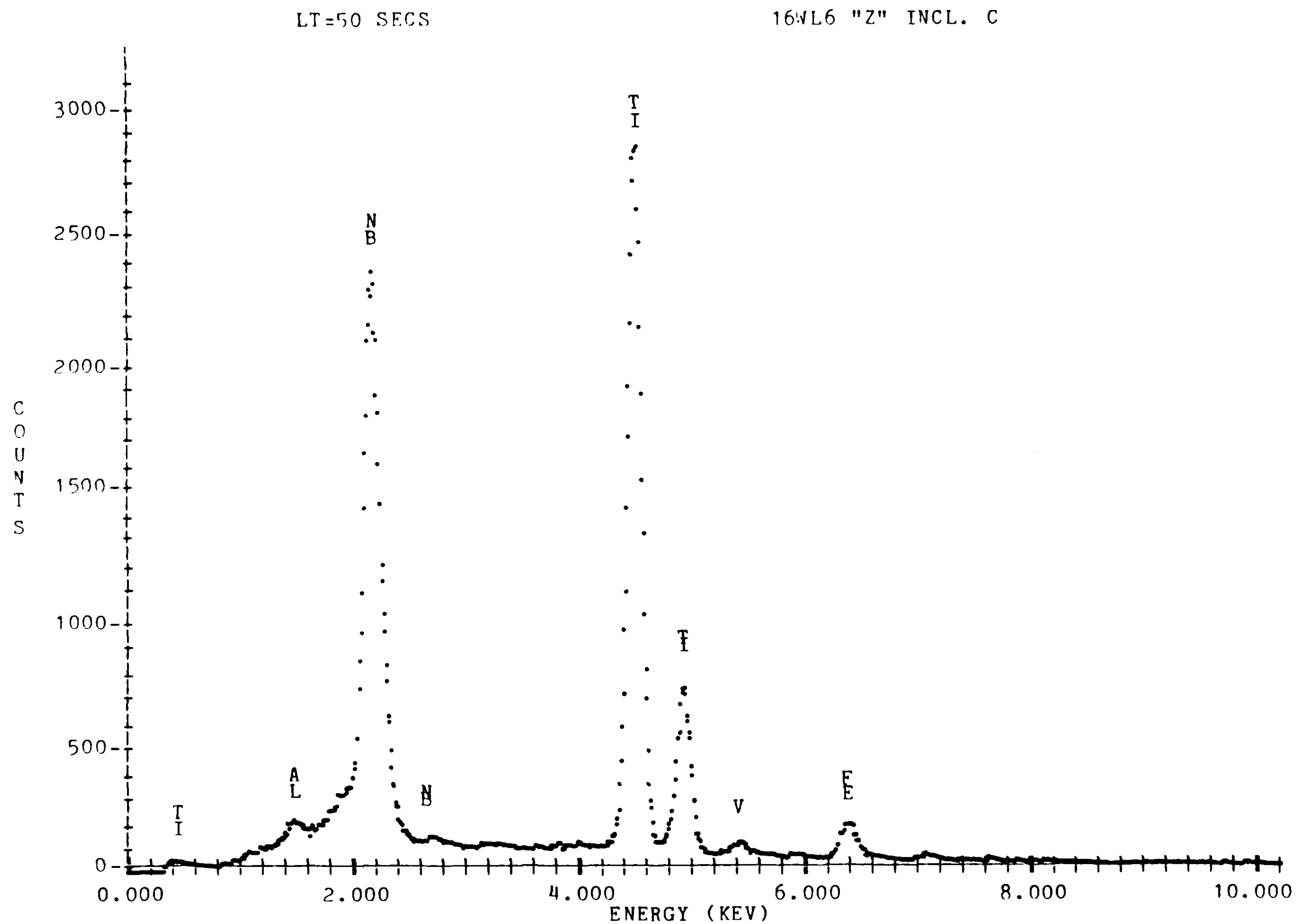


FIGURE 26: EDX-A Spectra from Inclusion "C" in Figure 25a

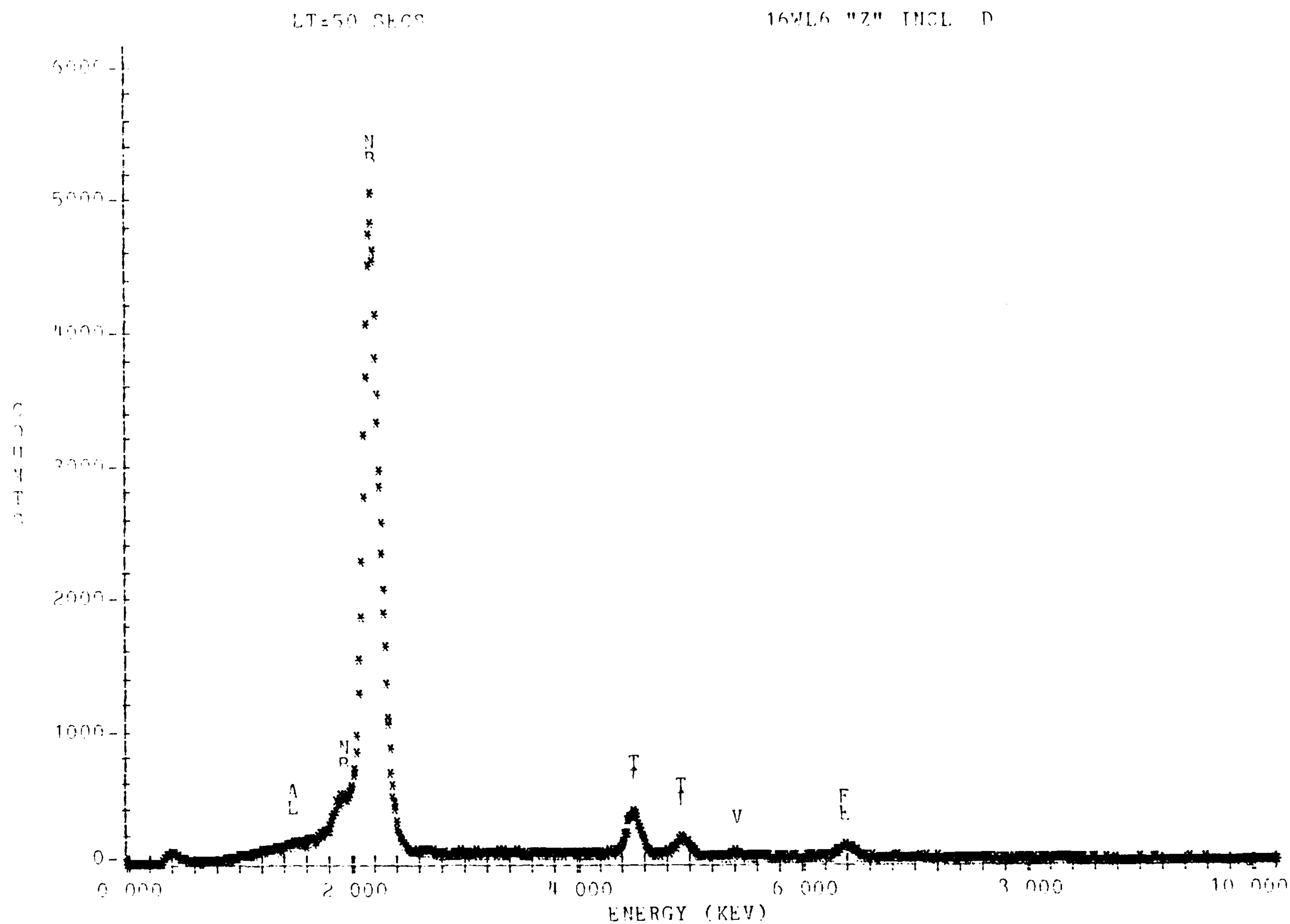


FIGURE 27: EDX-A Spectra from Inclusion "D" in Figure 25a

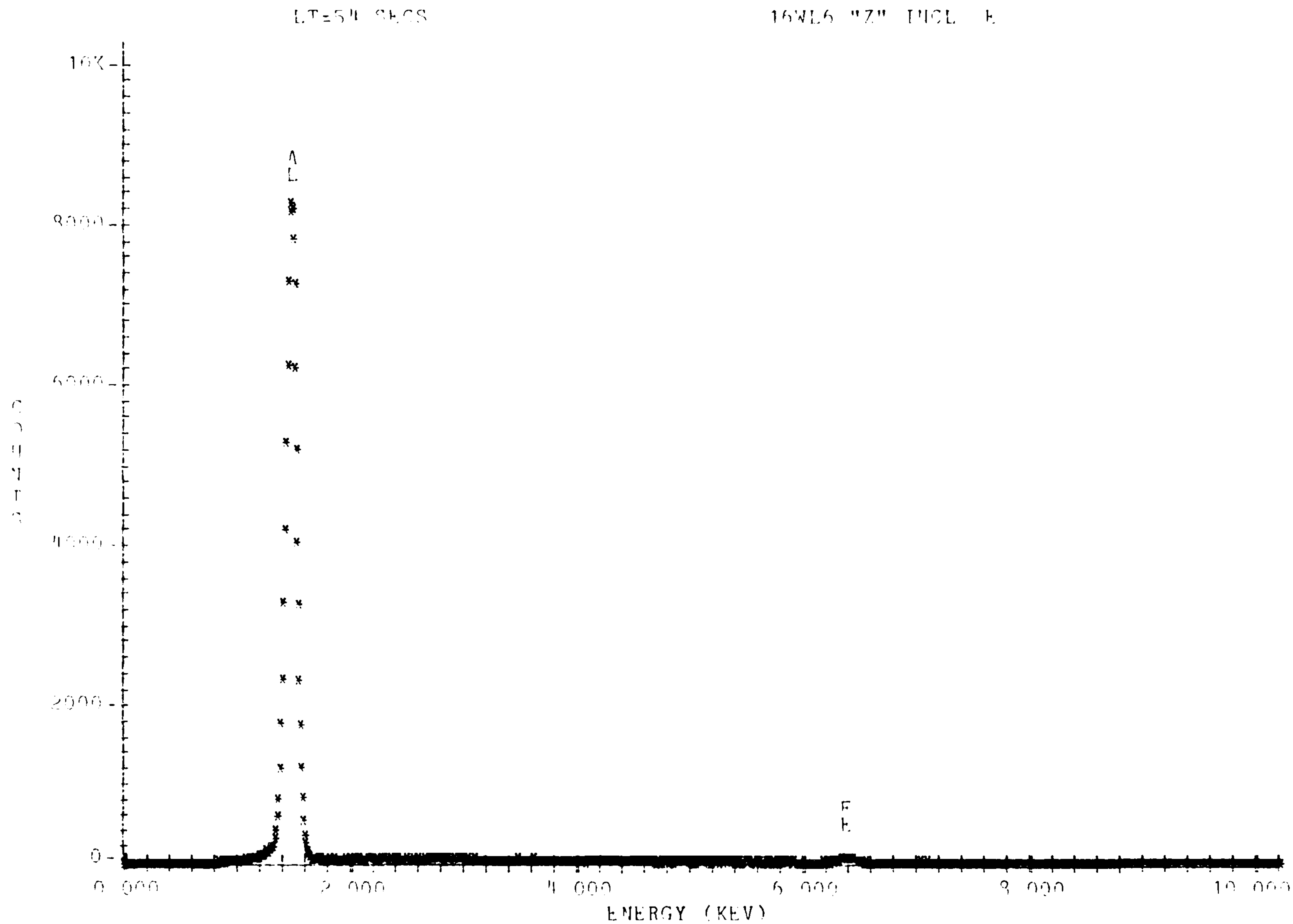
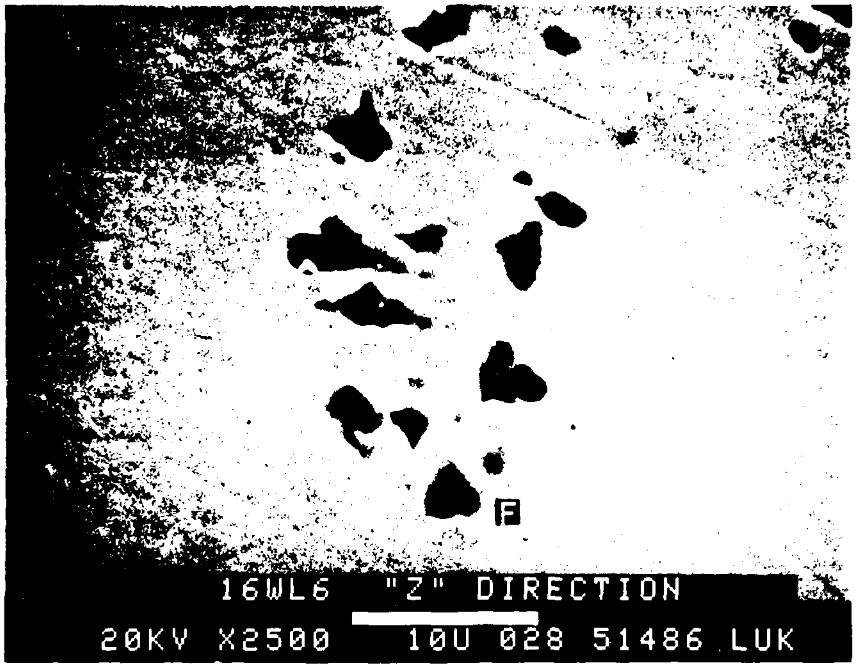


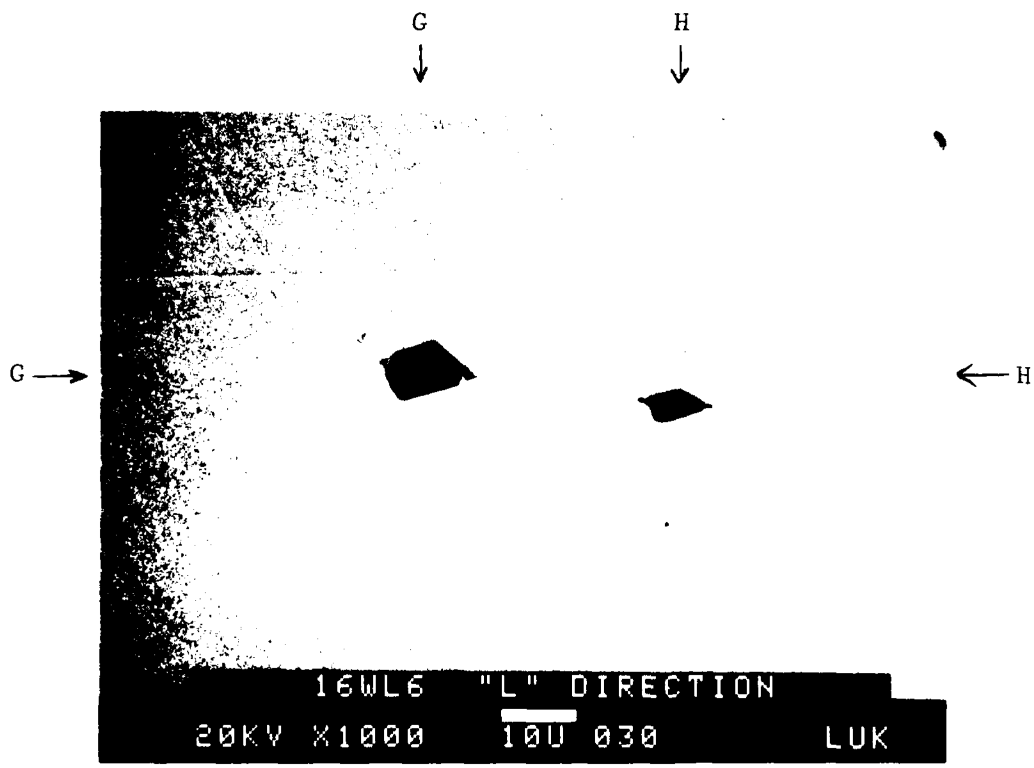
FIGURE 28: EDX-A Spectra from Inclusion "E" in Figure 25b



a) Sample 16W

Orientation S

2500X



b) Sample 16W

Orientation L

1000X

FIGURE 29: Inclusion Viewed on A Plane Normal to The Thru Thickness Direction

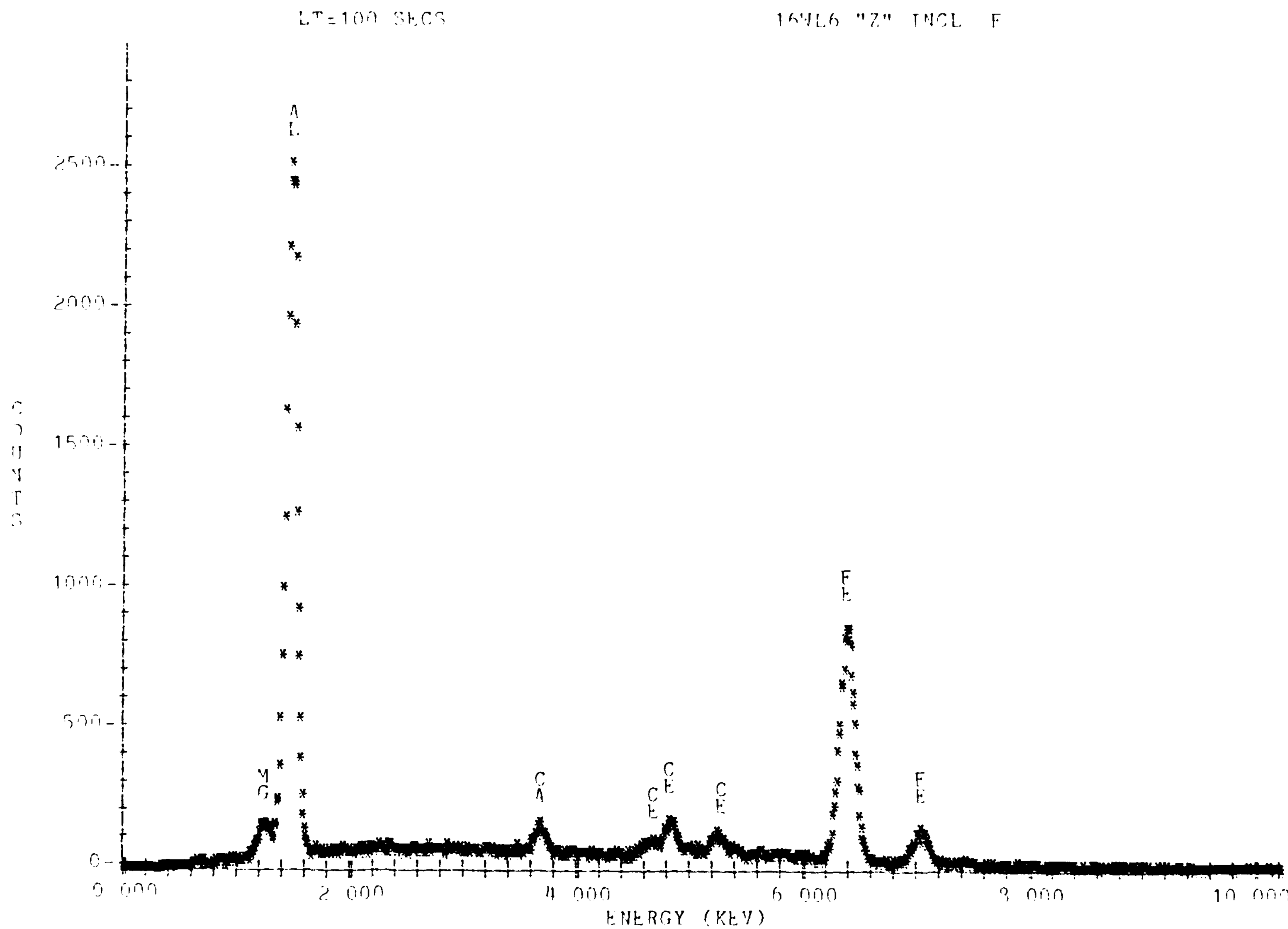


FIGURE 30: EDX-A Spectra from Inclusion "F" in Figure 29a

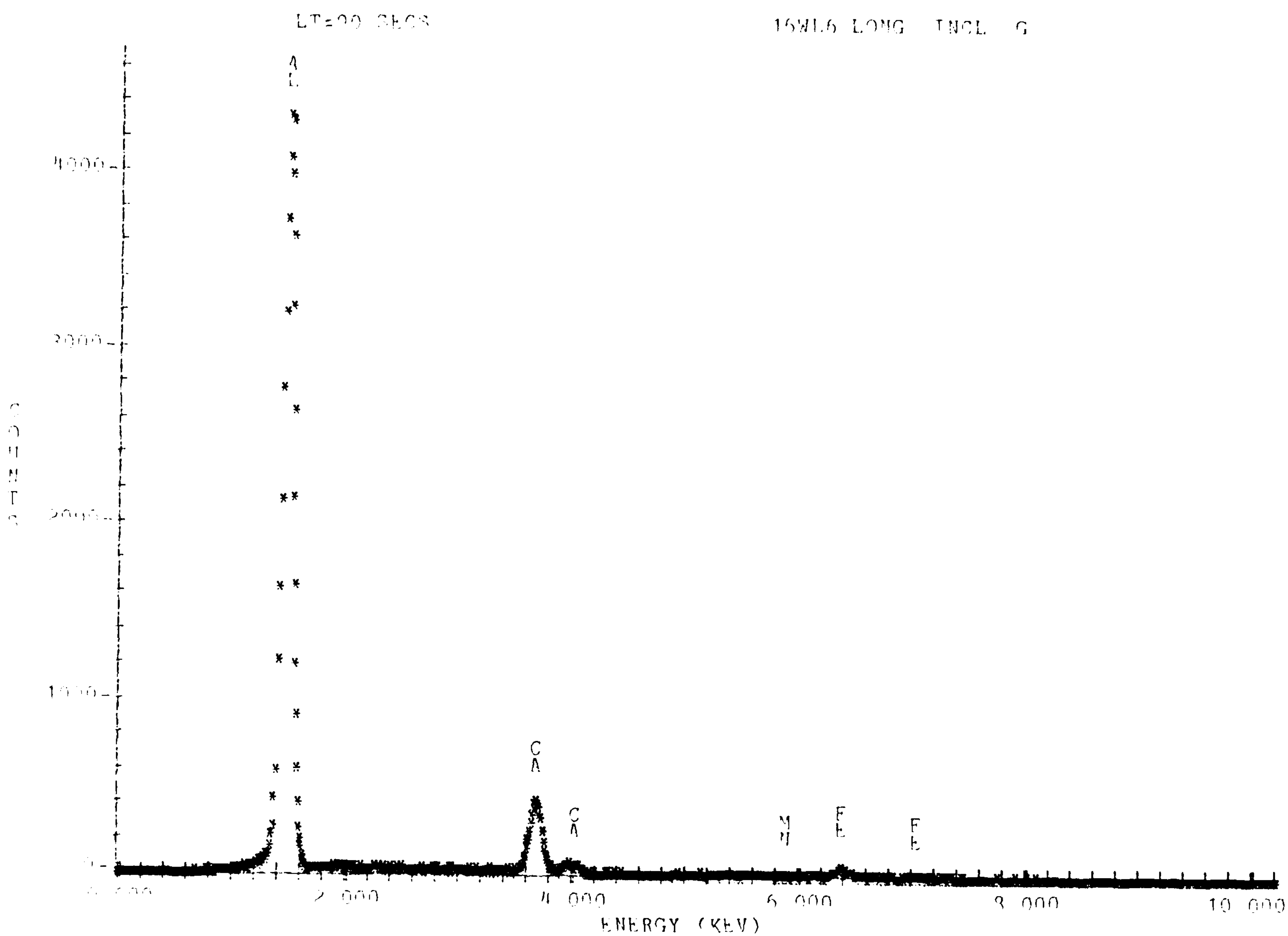
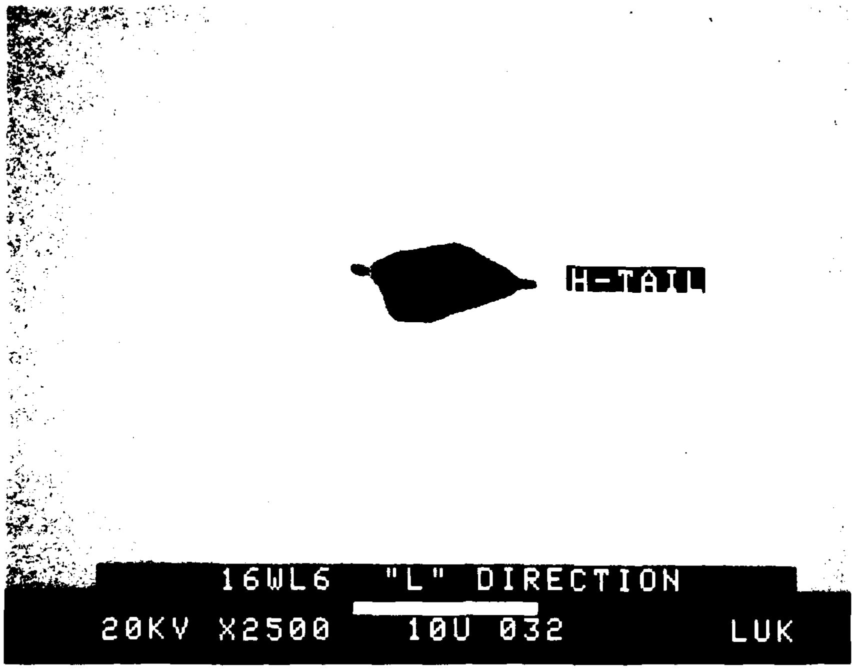


FIGURE 31: EDX-A Spectra from Inclusion "G" in Figure 29b



Sample 16W

Orientation L

2500X

FIGURE 32: Inclusion Viewed on Plane Parallel to The Longitudinal Rolling Direction

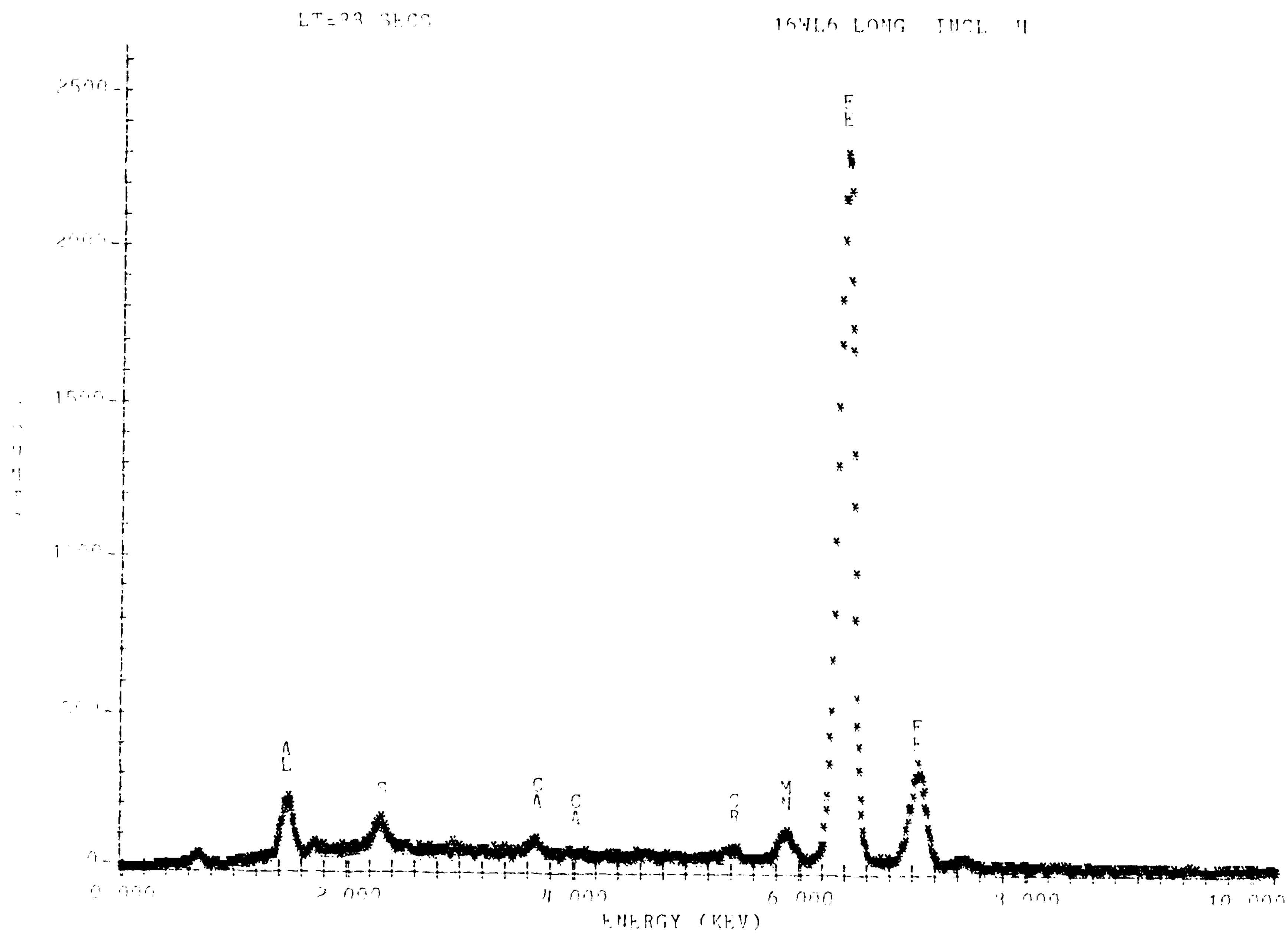


FIGURE 33: EDX-A Specrra from Inclusion "Tail" Shown in Figure 32

a) Sample 16W

Orientation T

2500X

b) Sample 16W

Orientation T

2400X

FIGURE 34: Inclusion Viewed on A Plane Parallel to The Transverse Rolling Direction

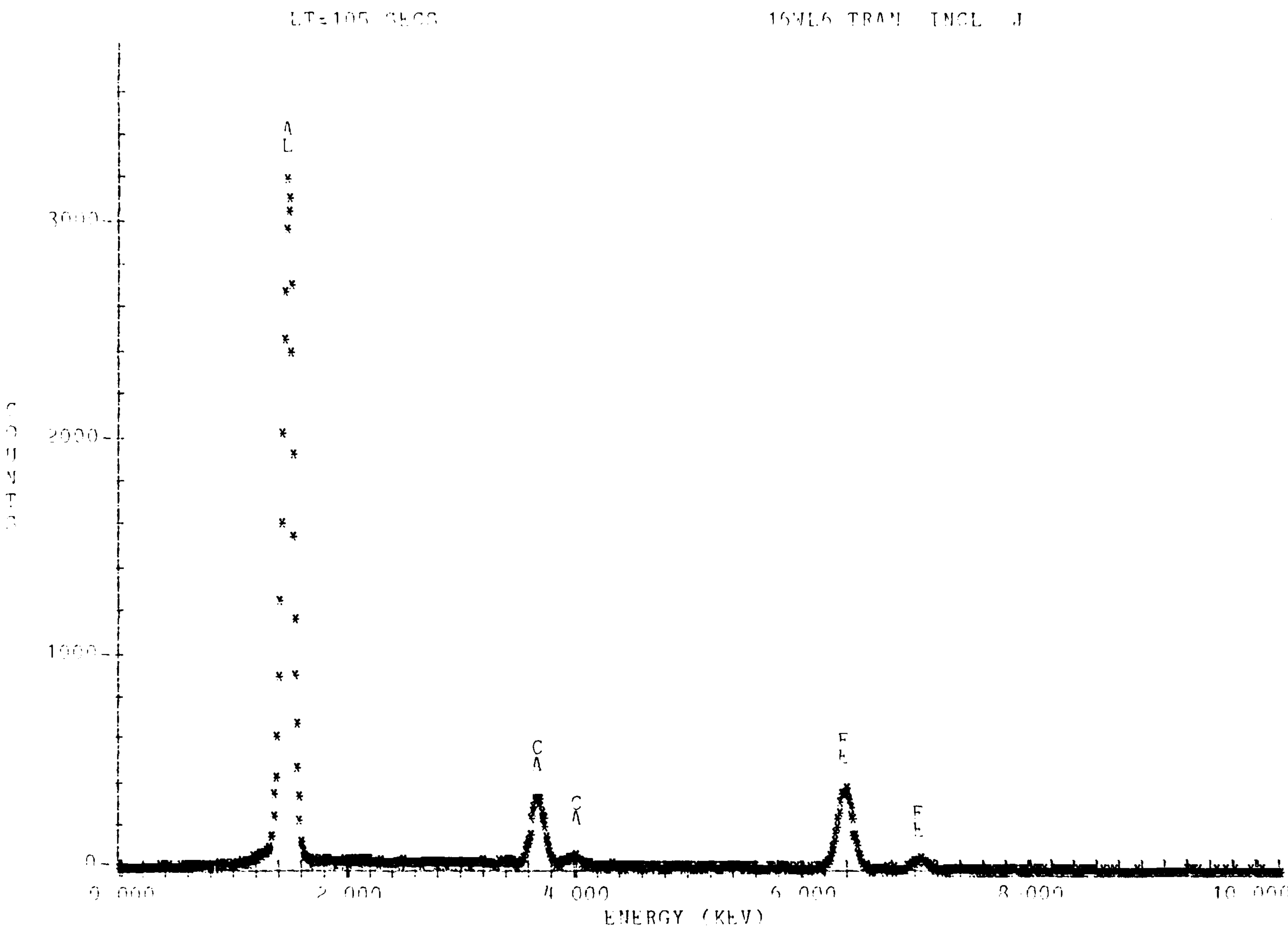


FIGURE 35: EDX-A Spectra from Inclusion "J" in Figure 34a

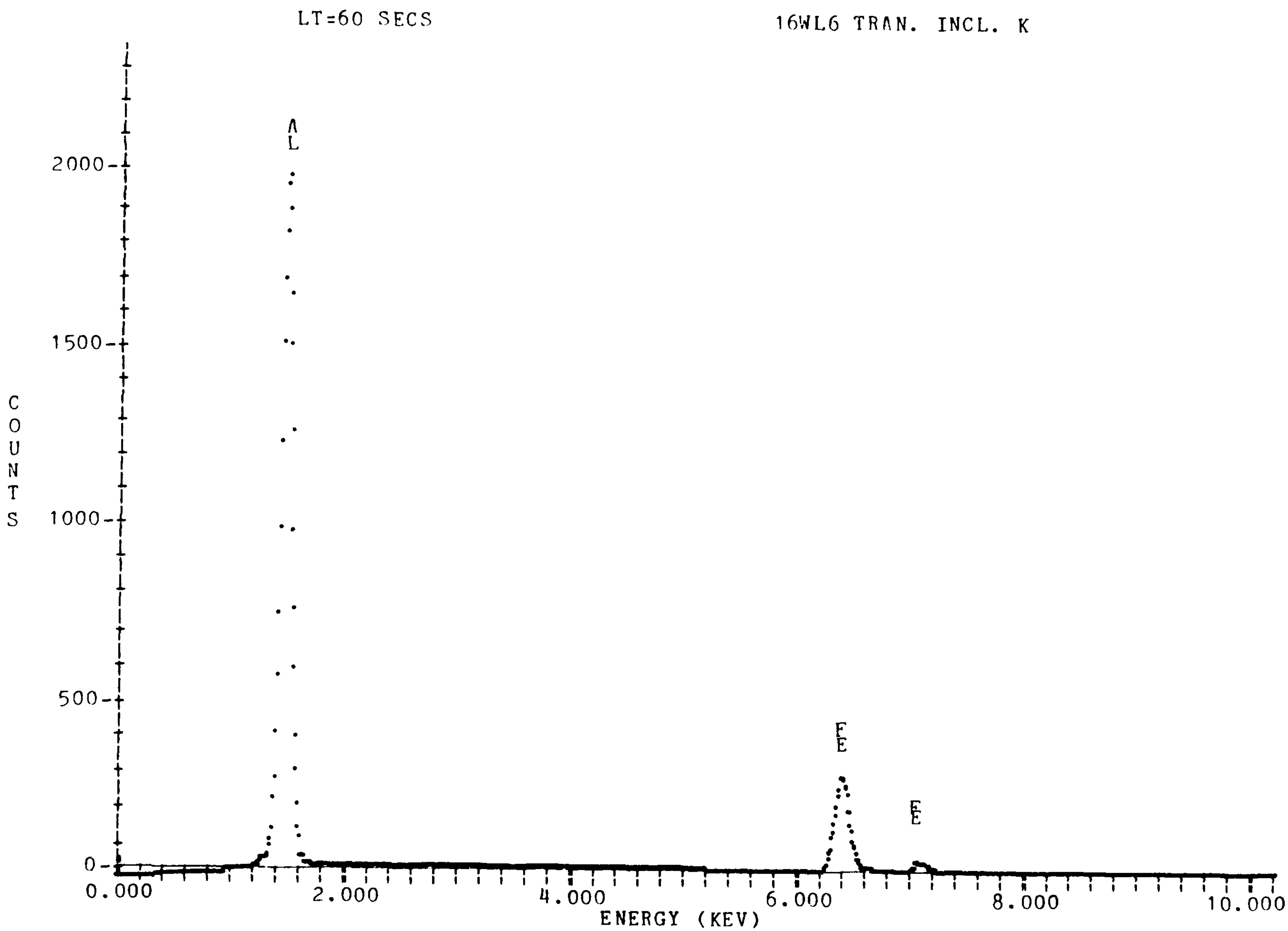


FIGURE 36: EDX-A Spectra from Inclusion "K" in Figure 34a

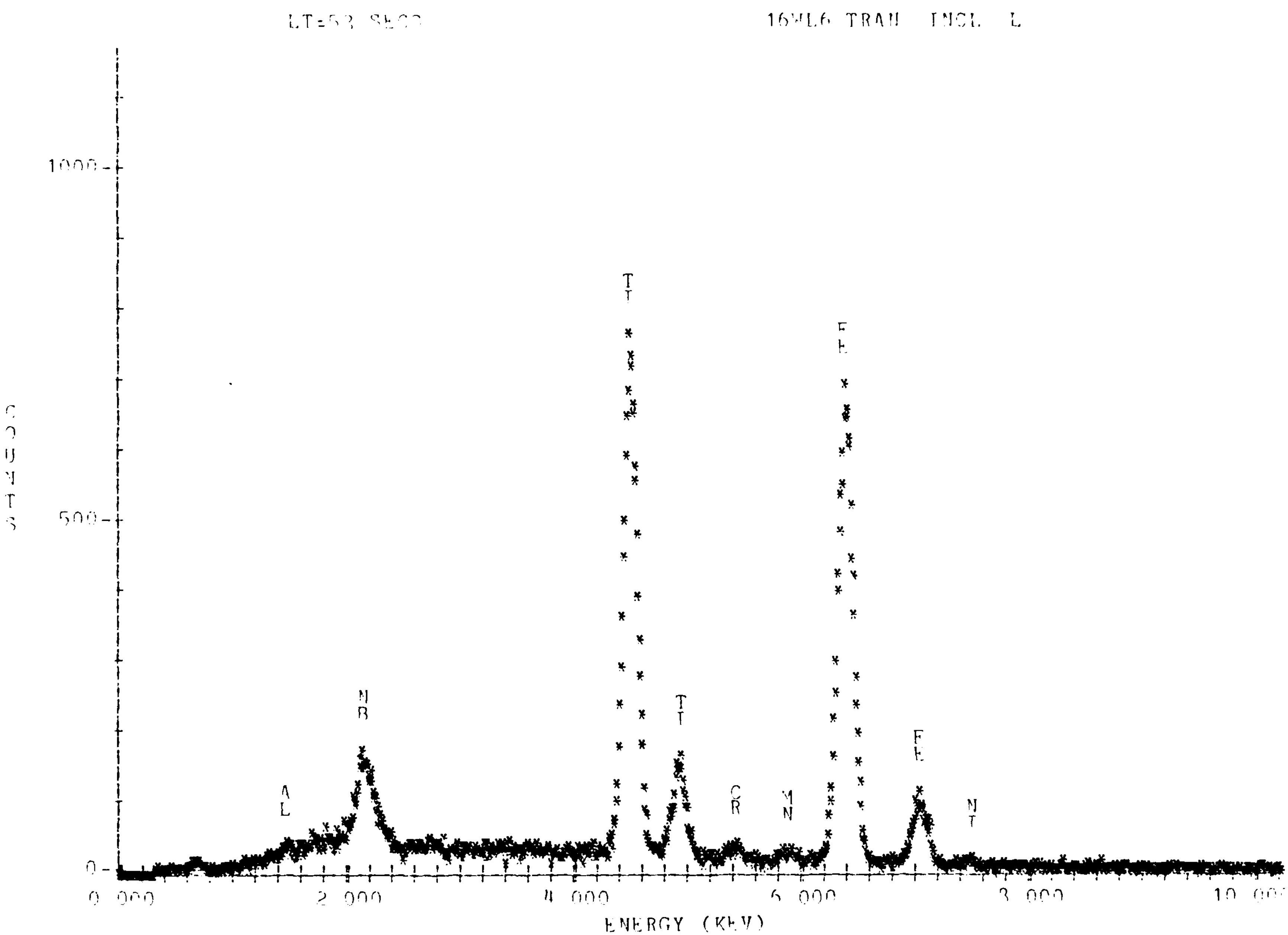
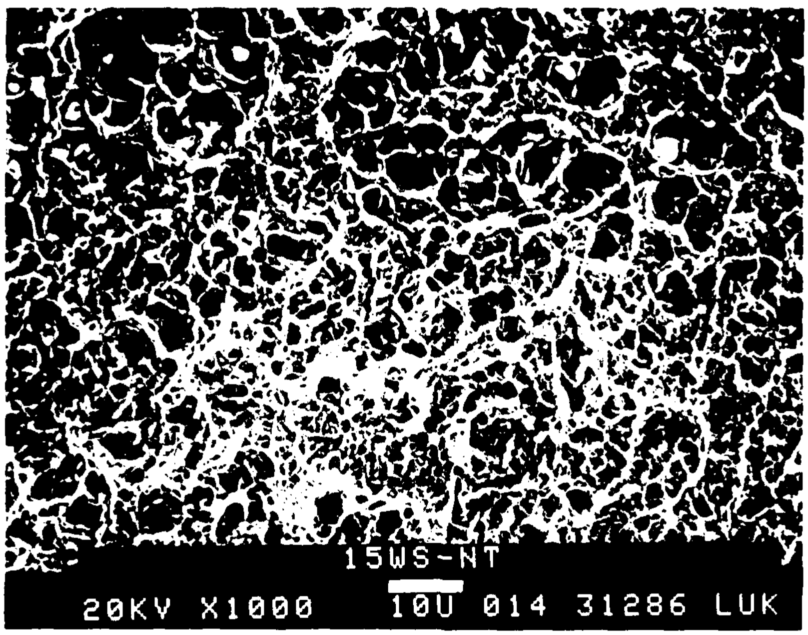


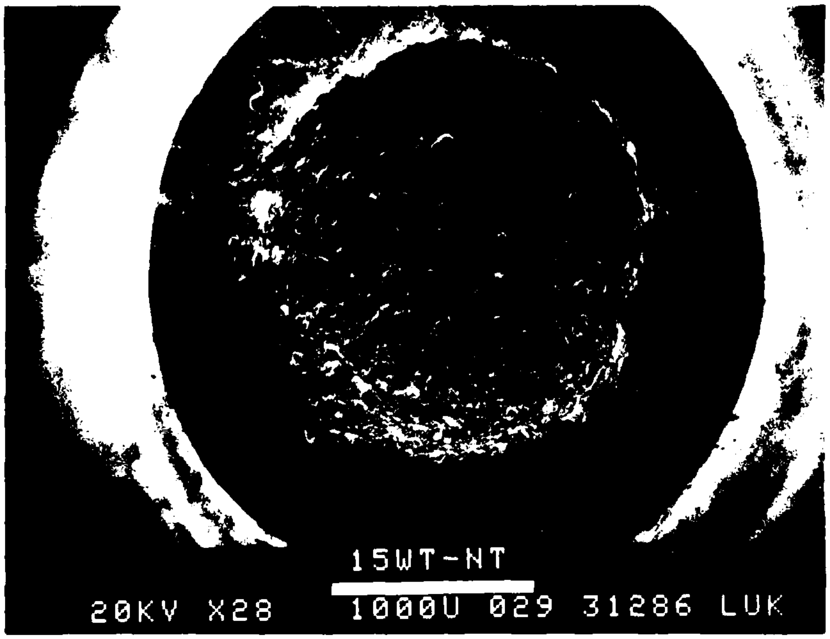
FIGURE 37: EDX-A Spectra from Inclusion "L" in Figure 34b

a) 25X

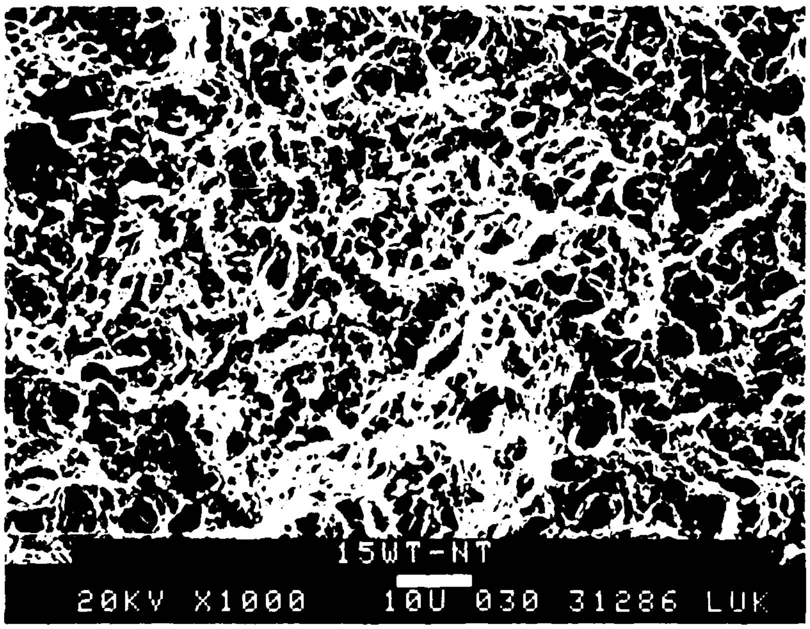


b) 1000X

FIGURE 38: Fracture Surface of Notch Tensile Sample 15WS. Water Quenched from 1550° F, Orientation S.



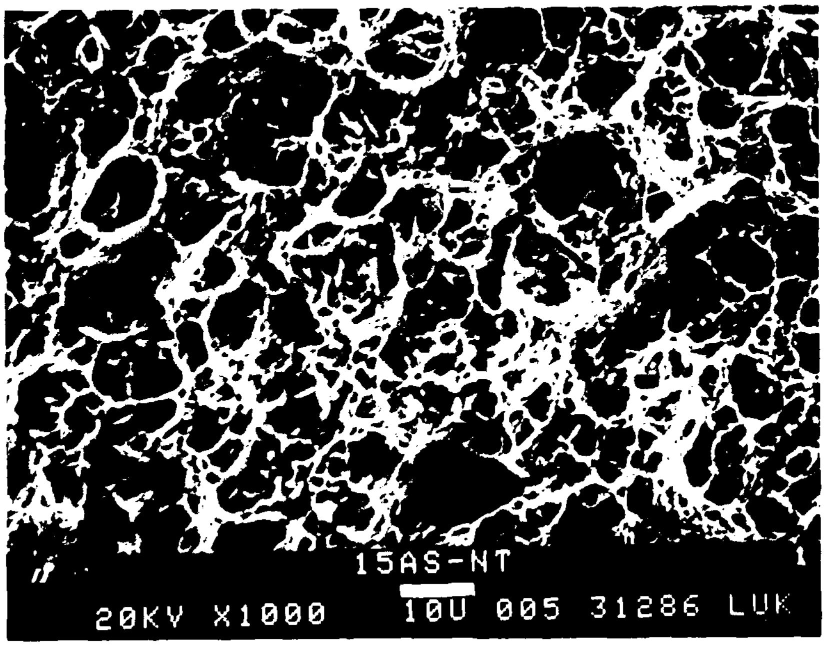
a) 28X



b) 1000X

FIGURE 39: Fracture Surface of Notch Tensile Sample 15WT. Water Quenched from 1550° F, Orientation S. Figure B at Center of Specimen Fracture Surface.

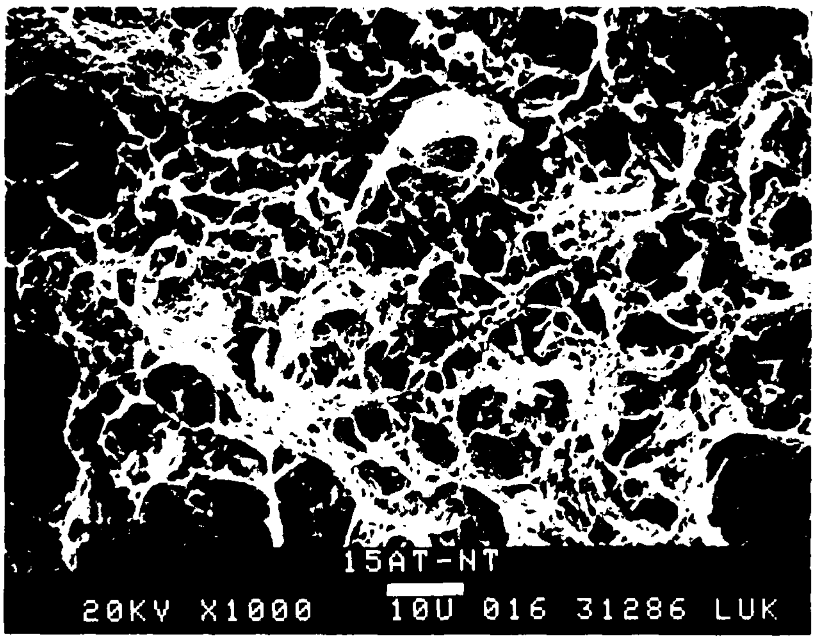
a) 25X



b) 1000X

FIGURE 40: Fracture Surface of Notch Tensile Sample 15AS. Cooled 100° F per Minute from 1550° F, Orientation S. Figure B A Center of Specimen Fracture Surface.

a) 26X



b) 1000X

FIGURE 41: Fracture Surface of Notch Tensile Sample 15AT. Cooled 100° F per Minute from 1550° F, Orientation T. Figure B at Center of Fracture Surface.

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THE EFFECT OF AUSTENITIZING CONDITIONS
ON THE ANISOTROPIC EMBRITTLEMENT OF
ESR 4340 STEEL
E. G. Hamburg and A. D. Wilson
Lukens Steel Company
Research Center
Coatesville, PA 19320
Technical Report MTL TR 86-44, October 1986
54 pp-illus.-tables, Contract DAAG46-85-C-0011
D/A Project 1A4632150079
Final Report, January 1985 to October 1986

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The effect of austenitizing conditions on the anisotropic embrittlement of electroslag remelted (ESR) 4340 steel were studied. Increasing austenitizing temperature from 1550°F to 1750°F had little or no effect on the strength and toughness of ESR melted 4340 steel. Decreasing the quench rate from 1000°F per minute to 500°F per minute had no effect on the strength and toughness. Decreasing the quench rate from 500°F per minute to 100°F per minute had a significant effect on Charpy V-notch toughness. Lower Charpy V-notch toughness associated with the quench rate of 100°F per minute was due to the presence of bainite in the microstructure. The presence of bainite had a small effect on slow bend fracture toughness. Plate anisotropy was very small in the plane of the plate (longitudinal versus transverse). Properties normal to the plane of the plate were affected drastically. Charpy V-notch toughness was decreased as much as 56% over the values obtained in the longitudinal direction. Reduction in area of the mild notch tensile specimen was decreased as much as 64% in the through-thickness direction when compared to the longitudinal direction. Inclusion clusters were primarily alumina with some calcium present. In all the tests conducted, there was no evidence for anisotropic embrittlement of this material (i.e., intergranular fracture).

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